Wake Manipulation Using Control Cylinders in a Tandem Arrangement

S. Rajagopalan, N. Lefeuvre, R. A. Antonia and L. Djenidi

Abstract The drag reduction phenomenon of a circular cylinder is investigated, using an X-wire probe, by placing a smaller diameter control cylinder of either circular or square cross-sectional upstream of the main circular cylinder. The separation between the two cylinders was chosen so as to minimise the overall drag of the main cylinder. Although both configurations resulted in drag reduction, the square control cylinder yielded a bigger reduction and had a greater impact on the mean velocity and turbulent velocity fluctuations in the wake. Both control cylinders led to a reduction in the wake half-width. Spectra in the near wake did not indicate any suppression in vortex shedding.

Keywords Wake control · Cylinder wake · Tandem

1 Introduction

The drag of a circular cylinder and the vortex shedding phenomenon have been extensively investigated because of their importance in aerodynamic flows (Alam et al. 2011; Hu and Zhou 2008). Significant attention is now being focused on controlling the vortex shedding as well as reducing the drag by placing a control cylinder upstream of the main cylinder. The diameter of the control cylinder is generally smaller than that of the main cylinder. However, there have been few systematic investigations of the wake characteristics, such as mean velocity and turbulent velocity rms distributions, downstream of the main cylinder associated with the drag reduction phenomenon. The main aim of the present study is two-fold—firstly to investigate the drag reduction phenomenon by placing a small

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Y. Zhou et al. (eds.), *Fluid-Structure-Sound Interactions and Control*,
Lecture Notes in Mechanical Engineering, DOI: 10.1007/978-3-642-40371-2_23,
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diameter control cylinder upstream of the main cylinder and secondly to compare mean velocity, rms velocity fluctuations, and Reynolds stresses corresponding to the minimum drag configuration at several downstream locations with those for a single cylinder. The influence of the geometry of the control cylinder—e.g., circular, square, triangular and channel cross sections—on the drag reduction, vortex shedding, and wake turbulence characteristics is another objective of the present study although only results for circular and square control cylinders are given here.

2 Experimental Conditions

Measurements were made in a 2.2-m-long and 0.34 × 0.34 m test section of a low-speed wind tunnel at a Reynolds number $Re_D = 7{,}500$ based on the main cylinder diameter D ($Re_D = U_0\, D/v$ where $D = 11.1$ mm and upstream velocity $U_0 = 10$ m/s). A 3-mm-diameter (d) control cylinder and a 3-mm-diameter square cylinder were used independently in the investigations. The control cylinders were placed upstream of the main cylinder on the centre line, and the separation between the two cylinders was varied by using two micrometre screws attached to the main cylinder. The drag of the main cylinder was estimated from surface pressure distribution and the drag of the combined cylinder arrangement was estimated from mean velocity measurements at $x/D = 40$ where x is the longitudinal distance measured from the centre of the main cylinder. Figure 1 shows the experimental arrangement. An X-probe with 5-μm-diameter Pt-10 % Rh hot wires was used to measure mean velocity and longitudinal (u) and lateral (v) velocity fluctuations at several y locations for $10 \leq x/D \leq 40$.

3 Results and Discussion

The gap between the cylinders that minimises the overall drag (for the tandem arrangement) was determined by measuring the difference in the (centre line) surface pressure between the upstream and downstream sides of the main cylinder for different values of Δx. It was observed by Rajagopalan and Antonia (2007) that

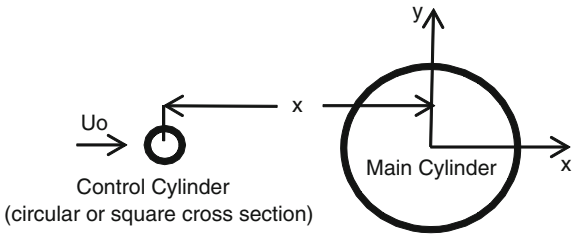


Fig. 1 Experimental arrangement

the value of Δx which minimises the pressure difference also yields minimum wake width and minimises the overall drag. For the circular control cylinder, the minimum drag was obtained for $\Delta x = 1.8D$, which is in agreement with the literature (Zdravkovich 1977a, b; Lee et al. 2004). The corresponding optimum Δx for the square control cylinder is $1.75D$. Note that the optimum value of Δx depends in general on the ratio d/D and Re_D.

To investigate the influence of the gap on the wake structure, both mean velocity (U) and longitudinal (u) and lateral (v) velocity fluctuations were measured at several downstream distances. Figure 2 compares the distributions of U at three downstream locations $x/D = 10$, 20, and 40. With the control cylinders, U tends to increase thus causing a decrease in the wake defect. This is qualitatively consistent square cylinder yields a larger drag reduction as is evident from the U distribution. Distributions of u' and v' (the prime denotes an rms value) at $x/D = 10$ and 40 are shown in Fig. 3 where a reduction in u' and v' can be observed when the control cylinders are used. At $x/D = 10$, v' is larger than u' whereas the opposite trend occurs at $x/D = 40$. As mentioned earlier, it was observed in Rajagopalan and Antonia (2007) that, at $x/D = 40$, the wake half-width exhibited a minimum for $\Delta x/D = 1.8$, suggesting that the minimum overall drag corresponds to a minimum half-width. Both Figs. 2 and 3 indicate a reduction in the wake half-width with the introduction of the control cylinders, as observed by Rajagopalan and Antonia (2007). However, Estimates of the wake half-width from mean velocity distributions at $x/D = 10$, 20, and 40 are shown in Fig. 4.

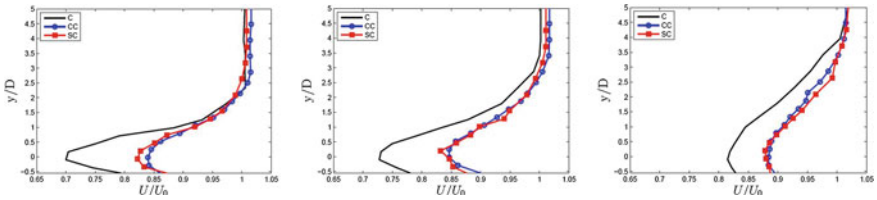


Fig. 2 *C* main cylinder only (*black*), *CC* circular control cylinder (*blue*), *SC* square control cylinder (*red*)

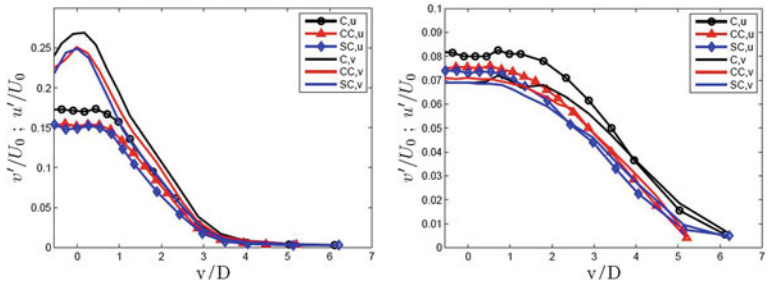


Fig. 3 Distributions of u' and v' at $x/D = 10$ (*left*) and 40 (*right*)

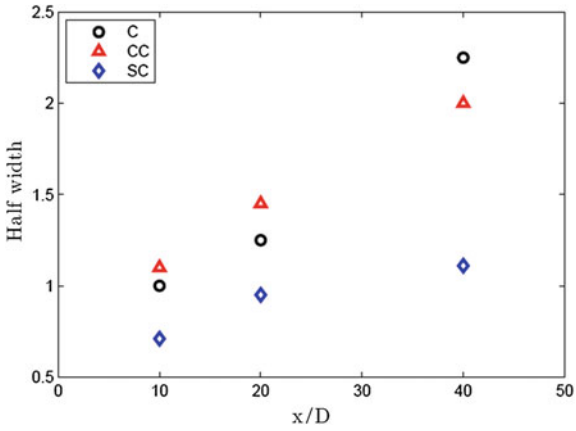


Fig. 4 Streamwise variation of wake half-width

Once again, it can be seen that square the control cylinder has the maximum influence on the wake development as it yields the minimum wake half-width. At $x/D = 10$ and 20, the half-width of the undisturbed cylinder wake is slightly smaller than that with the circular control cylinder. However, at $x/D = 40$, the half-width of the single circular cylinder is larger than that for either tandem arrangement. Based on hot-wire measurements in a cylinder wake Antonia and Rajagopalan (1990) identified $x/D = 30$ as the minimum location where the contributions from the Reynolds normal stresses become negligible. At this location, a momentum balance can be applied to determine the drag as the velocity defect is fully representative of the cylinder drag. Values of the drag coefficient C_D, estimated from U distributions at $x/D = 40$, were 1.3, 0.97, and 0.75 for the main cylinder and for the circular and square control cylinder arrangements, respectively. Spectra of u at $x/D = 10$ at a value of y aligned with the top edge of the main cylinder are shown in Fig. 5. There is a local peak at approximately 200 Hz which yields a Strouhal number $St_D = 0.22$, in agreement with established values for a circular cylinder. However, the introduction of the control cylinders does not suppress the formation of wake vortices. On the contrary, the amplitude of the peak at 200 Hz is increased by the control cylinders, the square cylinder having the largest effect. This suggests that the intensity of the vortices produced by square cylinder is larger than that in the other two wakes, which results in a reduction in the mean velocity gradients. This is supported by the measured mean velocity distributions. Figure 6 shows distributions of the Reynolds shear stress ($\overline{uv}$) at $x/D = 10$ and 40 for the three arrangements. At $x/D = 10$, the circular control cylinder yields a maximum in $\overline{uv}$ indicating enhanced mixing whereas the square cylinder produces a minimum value of $\overline{uv}$, which seems consistent with the magnitudes of the half-width at $x/D = 10$. At $x/D = 40$, $\overline{uv}$ values for the single cylinder are larger than the other two, the square cylinder yielding the smallest values. Once again, the nature of this distribution is consistent with the values of the wake half-width at this location. Clearly, the relative peak values of $\overline{uv}$ in the

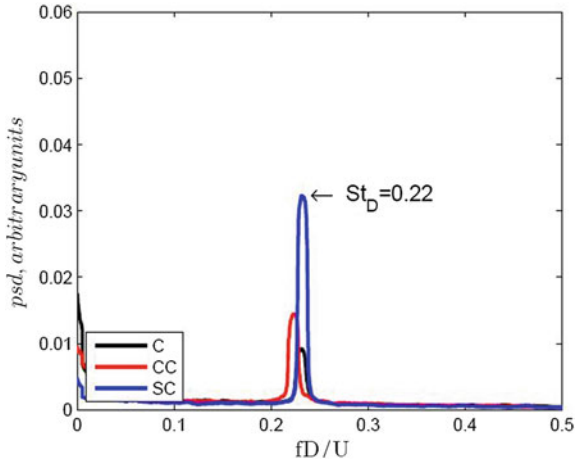


Fig. 5 Spectra of u at $x/D = 10$

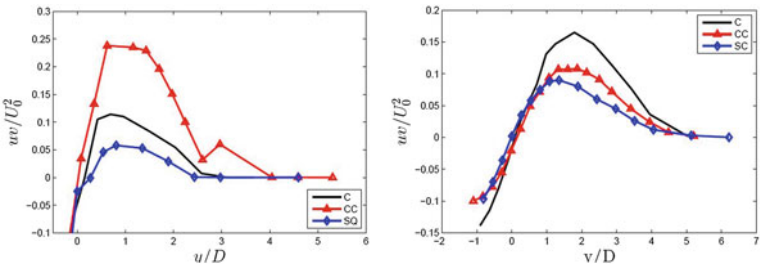


Fig. 6 Distributions of the Reynolds shear stress across the wake at $x/D = 10$ (*left*) and 40 (*right*)

three different cases reflect the difference in momentum transfer (or turbulent mixing) and hence the drag.

4 Conclusions

Measurements in the wake of a circular cylinder show that with the insertion of a circular or square control cylinder upstream of the main cylinder, mean velocity distributions exhibit a fuller profile for the tandem arrangement compared with that for a single cylinder. This results in a reduction in the wake half-width and a smaller drag for the tandem arrangement. Rms turbulence intensities are reduced in the modified wake. Spectral measurements support the presence of a more intense wake vortex for the tandem arrangement compared to a single cylinder suggesting more effective mixing between the outer higher-velocity fluid and the

inner lower-velocity fluid. This scenario is consistent with the observation of a 'fuller' mean velocity (reduced wake defect) profile in the tandem arrangement. Although the Reynolds shear stress distributions can only be considered as preliminary at this stage, they show that the square control cylinder leads to a smaller value of $\overline{uv}$ and reduced turbulent mixing, in apparent agreement with the observation of a reduction in the wake half-width. The square control cylinder has a larger influence on the wake development compared to the circular control cylinder.

Acknowledgments The support of ARC and the technical assistance of Ken Sayce are acknowledged.

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