Modification of a Square Cylinder Wake through a Secondary Upstream Cylinder

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Abstract. One of the inherent characteristics of a bluff body is the large drag coefficient even at a relatively low velocity. The condition is made worse when the flow separates from the body, and a time-dependent flow occurs downstream of the body; i.e. a vortex shedding phenomenon. It has been shown that suppression of the vortex shedding can significantly reduce drag coefficient of the bluff body. The present study investigates the intensity of the resulting laminar wake of a single and two square cylinders in tandem arrangement, where the intensity was measured through the lift force signals. The findings indicated that the presence of the secondary cylinder significantly altered the magnitude of lift force of the cylinder system, particularly at high Reynolds numbers under the laminar flow regime. Furthermore, the magnitude of lift force was lower when the secondary cylinder was separated from the main cylinder as compared to the case where both cylinders were attached.

1. Introduction

The first Studies on vortex shedding of bluff bodies and analysis of flow separation have been a topic of interest due to their fundamental significance and practical importance in some engineering applications such as aerodynamics and hydrodynamics. Examples of such applications are vibration of pipelines lying on the sea bottom under the influence of currents and waves, bridges, interaction of currents and waves with offshore structures, flow tubular or tube banks heat exchangers, skyscrapers, chimneystacks, suspension bridges and chimneys near tall buildings, structures in the atmospheric boundary layers and submarine pipe see e.g., [1], [2], [3], [4] and [5].

These bluff bodies might experience unsteady loads due to the flow separation and formation of the wake region and vortices. By controlling the wake structures and flow separations, the unsteady forces experienced by the bluff bodies is significantly reduced. The unsteady forces due to the vortex shedding induce various effects such as mixing enhancement, vibration and noise production, structural system resonance and scouring. Depending on the target application, the effects can be beneficial or harmful, and others could be even detrimental. In the latter case, the strategy of vortex shedding suppression should be implemented clearly.

Various control methods have been suggested to control the wake structure and vortex shedding, such as using current injection [6], utilizing an external small element [7], using rotary oscillations [8], generating a secondary flow (suction, blowing, bleed, and synthetic jets) [9], modifying surface roughness [10], using thermal effects [11] and adding add on devices [12]–[14]. These approaches fall into two major categories, which are passive and active control methods. The active control method requires some external energy to alter the fluid flow characteristics, while passive method does not require any external energy which is simpler to implement than that of the active method.

[15] has performed a numerical study of vortex shedding behind a bluff body for flow at low Reynolds number by placing a relatively smaller control cylinder placed in the wake region of the main
bluff body. Computed results showed that the shear layer stabilized with the presence of the control cylinder and the local favorable pressure gradient was produced by the control cylinder in the wake region of the flow. [16] also employ a similar approach to suppress the vortex shedding of a bluff body by using a rectangular or square cylinders placed upstream of a square bluff body. The results showed that the drag force decreased with the height of the upstream bluff body for a specific gap height (distance between the cylinder and wall).

In the context of passive flow control approach, the effective zone (location element the wake where vortex shedding can be suppressed, and the drag and lift fluctuation can massively decrease) is still not well configured or understood due to the sensitivity of the passive method to the bluff body arrangements. In addition, there is still lack of square bluff bodies wake control studies in the literatures. The present work seeks to examine the wake of and forces acting on a square cylinder subjected to an upstream flow condition due to the presence of a relatively small square control cylinder.

2. Methodology

In this investigation an internal flow of viscous fluid over square cylinders in tandem arrangement in a rectangular duct was considered (as depicted in Figure 1). A benchmark case (Case 0) of a single square cylinder with side length $d$ in the domain was also considered in this study. For the case of two square cylinders in tandem, a small cylinder of size $0.5d$ was placed upstream of a large cylinder of size $d$. For the first case, both cylinders were attached (Case 1), as shown in Figure 1(a), while for the second case (Case 2), both cylinders were separated with a centre-to-centre gap of $1.25d$, as shown in Figure 1(b). A fully-developed flow was imposed at the inlet boundary and a Neumann boundary condition of zero pressure gradient was imposed at the outlet boundary. All other boundaries were set to no-slip condition.

The meshes were constructed in such a way that elements are adequately small near boundaries in order to properly resolve high velocity gradients at the boundaries, as depicted in Figure 2. The flow was set as laminar and the governing equation was solved using a SIMPLE scheme for pressure-velocity coupling.

Figure 1. Schematic diagram of the system under investigation. The control cylinder is either (a) attached (Case 1) to or (b) separated from the main cylinder (Case 2).

Figure 2. A typical mesh with two cylinders in tandem configuration, extends $2.5d$ upstream and $7.5d$ downstream.
3. Results and Discussion

Flows over cylinders with different configurations were simulated for Reynolds numbers ranging between 50 and 200, with the increment of 50. At $Re = 50$, flows in all configurations were stable, i.e. no time-dependent wakes behind the cylinder. This can be clearly seen in the plot of lift coefficient (a typical example for Cases 0 (indicated by a blue solid line) and 1 (indicated by grey solid and dashed lines) are shown in Figure 3(a) and Figure 3(b)), where there is no fluctuation in the signal of lift force. When $Re$ is increased to 100, the single cylinder case shows a time-periodic wake in the downstream flow. This wake flow caused a periodic fluctuation of positive and negative lift forces experienced by the cylinder, as indicated by the sinusoidal fluctuation of the lift force in Figure 3(c). However, for Case 1, the lift force signals for both cylinders show very little periodicity with much smaller magnitude than that of Case 0. This observation indicates that the presence of a small cylinder attached to the upstream side of the main large cylinder tends to delay the onset of full periodicity of vortex shedding. For Case 2 however, there is no sign of fluctuating lift force even until $t = 60s$, where $t$ is flow simulation time (as shown in Figure 3(d)).

When $Re$ is increased to 150, it is observed that the flows reach a fully-periodic state as early as $t \approx 30s$, as depicted in Figure 4(a). For Case 1, the main cylinder experiences a fluctuating lift force with an amplitude similar to that of the single cylinder case. The amplitude of lift force for the secondary cylinder is, however, much lower than that of the main cylinder. This observation is attributed to the fact that the presence of the large cylinder downstream of the secondary small cylinder tends to inhibit the wake flow of the secondary cylinder, thus reducing the amplitude of lift force. The influence of the secondary cylinder is even more pronounced for Case 2, where the vortex shedding of both cylinders is almost attenuated at $Re = 150$ (the amplitude of the lift force is two to three orders of magnitudes smaller than that of Case 1 – as shown in Figure 4(b)).
When flow reaches $Re$ of 200, the amplitude of lift force exerted on the cylinder of Case 0 increases considerably, as depicted in Figure 4(c). For Case 1, the amplitude of lift force for both cylinders decreases by two orders of magnitudes compared to that of the $Re = 150$ case. In contrast, the amplitude of lift force exerted on both cylinders for Case 2 doubled when Reynolds number is increased from 150 to 200, as shown in Figure 4(d). However, it is important to note that the rms amplitude of lift force exerted on both cylinders for Case 2 is just 0.65% lower than that of Case 1 at this Reynolds number. This is due to the fact that the vortices shed at almost the same downstream distance for both cases and that the intensity of shed vortices is almost identical (as indicated in Figure 5).

4. Conclusion
Flow over a single and two square cylinders in tandem arrangement has been studied. Low Reynolds number producing laminar wakes were considered. It was shown that the presence of an upstream secondary cylinder modified the amplitude of lift force exerted on the main cylinder, except for when the secondary cylinder is attached to the main cylinder at $Re = 150$ and for Reynolds number in which
the wake of a single cylinder is steady. Furthermore, the presence of this secondary cylinder tends to delay the onset of full periodicity of vortex shedding at certain Reynolds number. It was also shown that the placement of a separated secondary cylinder upstream of the main cylinder was better at inhibiting time-dependent wakes as compared to the attached counterparts within the investigated Reynolds number range.

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