Ocean Engineering 94 (2015) 36–50

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Influence of wall proximity on flow around two tandem circular cylinders

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ARTICLE INFO

*Article history:*
Received 3 August 2013
Accepted 30 November 2014

*Keywords:*
Tandem cylinders
Wall proximity
Vortex shedding
Drag and lift coefficients
Spectrum of lift coefficient
Particle image velocimetry (PIV)

ABSTRACT

An experimental study was conducted to investigate the flow around two tandem cylinders placed near and parallel to a plane wall. The Reynolds number based on the cylinder diameter ($D$) was 6300. The cylinder centre-to-centre spacing ratio ($L^*=L/D$) was varied from 1.5 to 6, and the gap-height-to-cylinder-diameter ratio ($G^*=G/D$) from 0.15 to 2. The flow fields were measured using Particle Image Velocimetry (PIV), in conjunction with measurements of fluid dynamic forces (drag and lift) on the downstream cylinder using load cell. The flow strongly depends on the combined value of $G^*$ and $L^*$. With reference to $G^*$, the flow could be classified as vortex-shedding suppression regime ($G^*<0.3$), intermediate-gap regime ($0.3<G^*<1$) where vortex shedding occurs but is influenced by wall proximity, and large-gap regime ($G^*>1$) where the wall influence becomes negligible. Similarly, three categories can be identified as a function of $L^*$, namely, extended-body regime $1<L^*<2$, reattachment regime at $2<L^*<4$, and impinging regime at $L^*>4$. Variations of dynamic drag and lift coefficients, spectra, Strouhal numbers, and Reynolds shear stress are also presented to characterize the different flow regimes in the $G^*$–$L^*$ plane.



## 1. Introduction

The interference of flow around two circular cylinders is of both academic interest and practical importance, see Sumner (2010) for a comprehensive review. Among the many possible arrangements of the two cylinders to be positioned in relative to the flow direction, the tandem configuration has been extensively studied. This type of interference, referred to as 'wake interference' by Zdrvkovich (1987), is a function of the inter-cylinder distance (expressed as the ratio between the centre-to-centre spacing and the cylinder diameter, $L^*=L/D$, thereafter abbreviated as the spacing ratio). Zdravkovich (1987) proposed that the flow can be classified into three basic types: (i) single bluff-body regime at small $L^*$ ($1<L^*<1.2\sim1.8$), where periodic von Kármán vortex shedding is observed only in the wake of the downstream cylinder; (ii) reattachment regime at moderate $L^*$ ($1.2\sim1.8<L^*<3.4\sim3.8$), where the shear layers emanating from the upstream cylinder reattach onto the surface of the downstream cylinder; (iii) impinging regime at large $L^*$ ($L^*>3.4\sim3.8$), where von Kármán vortices are shed from the upstream cylinder and periodically impinge on the downstream cylinder. Zhou and Yiu (2006) showed that the reattachment regime ($2<L^*<5$) can be further sub-divided into two distinct categories, for which the reattachment is on the rear and leading surfaces of the downstream cylinder, respectively (see Fig. 1). The exact values of $L^*$ to delineate the boundaries between different regimes depend on the value of Reynolds number (Carmo et al., 2010) and free-stream turbulence intensity (Ljungkrona et al., 1991). The critical spacing ratio ($L^*_{cr}$), at which periodic vortex shedding begins to occur from the upstream cylinder, varies from $L^*_{cr}=3$ to 5 in the literature (e.g., Lee et al., 2009). Correspondingly, the fluid forces on the cylinders would experience a discontinuous 'jump' at about $L^*_{cr}$ (Zdravkovich and Pridden, 1977). Moreover, Xu and Zhou (2004) showed that the vortex shedding frequency is dependent on Reynolds number over the range Re$=800$–$4.2\times10^4$ (Re$=UD/\nu$, where $\nu$ is the kinematic viscosity of fluid).

On the other hand, there are a number of engineering practices in which cylindrical structures are placed near a plane wall, such as submarine pipelines, risers and cables on seabed. To date, many researchers have examined the influence of wall proximity on a single cylinder with the cross-section of either circular (e.g., Bearman and Zdravkovich, 1978; Lei et al., 1999; Price et al., 2002; Dipankar and Sengupta, 2005; Nishino et al., 2007; Wang and Tan, 2008a; Lin et al., 2009; Sarkar and Sarkar, 2010; Ong et al., 2012; Wang et al., 2013), square (e.g., Wang and Tan 2008b; Mahir, 2009) or rectangular (e.g., Maiti, 2012; Maiti and Bhatt, 2014). The nearby wall affects not only the dynamic pressure and forces on the

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http://dx.doi.org/10.1016/j.oceaneng.2014.11.018
0029-8018/

cylinder, but also the wake pattern and flow-induced vibrations. The ratio between the gap height to the cylinder diameter ($G^*=G/D$, abbreviated hereafter as the gap ratio) is found to be the predominant parameter. The impermeability of the wall poses an irrotational constraint to the wake development, resulting in suppression of the classical von Kármán vortex shedding that is in absolute instability (Huerre and Monkewitz, 1990) below a critical gap ratio ($G^*_{cr}$). As sketched in Fig. 2(a), when $G^*<G^*_{cr}$, the wake is steady with a long recirculation region: while the gap flow keeps attached on the wall, the upper shear layer emanating from the cylinder exhibits as elongated Kelvin-Helmholtz (K-H) type of roll-ups (in convective instability). However, when $G^*>G^*_{cr}$ (Fig. 2(b)), the gap flow is strong enough to detach upward from the wall (or upwash), and to interact with the upper shear layer to form discrete vortices. It should be noted that the vortex shedding is asymmetric about the horizontal wake centerline; also, there is a coupling between the lower shear layer and the wall boundary layer, as reflected by the phenomenon that each anticlockwise vortex is accompanied by a small clockwise vortex in the near wall region. The value of $G^*_{cr}\approx 0.3$ slightly varies with Re and thickness of the wall boundary layer (e.g., Buresti and Lanciotti, 1992; Price et al., 2002).

However, little attention has been paid to the configuration of two tandem cylinders in proximity to a plane wall (see Fig. 3). The flow interference between the two cylinders is further complicated due to the presence of the wall boundary. Bhattacharyya and Dhinakaran (2008) numerically studied the 2-dimensional (2D) flow around two tandem square cylinders with a linear incident velocity profile at $G^*=0.5$ and $L^*=1.5$–6. The non-uniform approach flow causes difference in the strength of the upper and lower shear layers. The flow can be steady up to Re = 125 depending on the value of $L^*$. More recently, Harichandan and Roy (2012) simulated the flow around two near-wall tandem cylinders (circular/square) at Re = 100 and 200, $G^*=0.5$ and 1, and $L^*=2$ and 5. For a given Re, the Strouhal numbers of the two cylinders are identical, but the lift and drag coefficients are different.

As described above, there is limited information available on the flow around two tandem cylinders in proximity to a wall boundary. Two aspects need attention. Firstly, the only two published studies, namely, Dhinakaran (2008) and Harichandan and Roy (2012), were conducted at relatively low Re (up to 200), that is, in the laminar regime. Yet, in engineering practice the flow is generally in the subcritical regime. Secondly, both studies considered only a rather limited number of combinations of $G^*$ and $L^*$, and hence a complete picture in the $G^*$–$L^*$ plane is still unavailable. These motivate the present relatively systematic investigation for $0.15\le G^*\le 2$ and $1.5\le L^*\le 7$ under a constant Reynolds number in subcritical regime (Re = 6300).

## 2. Experimental set-up and methodology

The experiments were performed in a re-circulating open channel located at Maritime Research Centre, Nanyang Technological University, with a test section of 5 m × 0.3 m × 0.45 m (length × width × height). The channel bed and the two side walls of the test section were made of glass to allow for optical access. The free-stream velocity was uniform to within 1.5% across the test section, and the turbulence intensity in the free stream was below 2%.

Fig. 3 shows a sketch of the two tandem cylinders placed near and parallel to a plane wall. The cylinder models were made of smooth, transparent acrylic rod with an outer diameter of $D=15$ mm. During the experiments, the free-stream velocity was kept constant at $U=0.42$ m/s (Re = 6300). The approach boundary layer was fully developed with a thickness of $\delta=7$ mm ($\sim$ 0.5$D$). The cylinders' centre-to-centre spacing was varied as $L=22.5$, 30, 45, 60, 75, 90 and 105 mm ($L^*=1.5$–7), and the gap height $G=2.25$, 6, 9, 12, 21 and 30 mm ($G^*=0.15$–2). Therefore, totally 42 cases were considered in the present study.

The span ($b$) of the cylinders was 200 mm, leading to an aspect ratio (AR) of $b/D=13.3$. This value was considered to be large enough (AR ≥ 10 according to previous finding, for example, Lam and Zou, 2010) to ensure a nominally 2D flow in the near wake. Therefore, the velocity measurements with Particle Image Velocimetry (PIV) were performed in the mid-span plane. The origin of the coordinate system was located at the center of the upstream cylinder, with $x$, $y$ and $z$ denoting the streamwise, transverse and spanwise directions, respectively. The positive drag and lift forces are in the $x$- and $y$-directions, respectively.

Velocity measurements were performed using a digital PIV system (LaVision model). The flow field was illuminated with a double cavity Nd:YAG laser light sheet at 532 nm wavelength (Litron model, power ~ 135 mJ per pulse, duration ~ 5 ns). Sphericel® 110P8 hollow glass spheres (neutrally buoyant with a mean diameter of 13 μm) were seeded in the flow as tracer particles. The images were

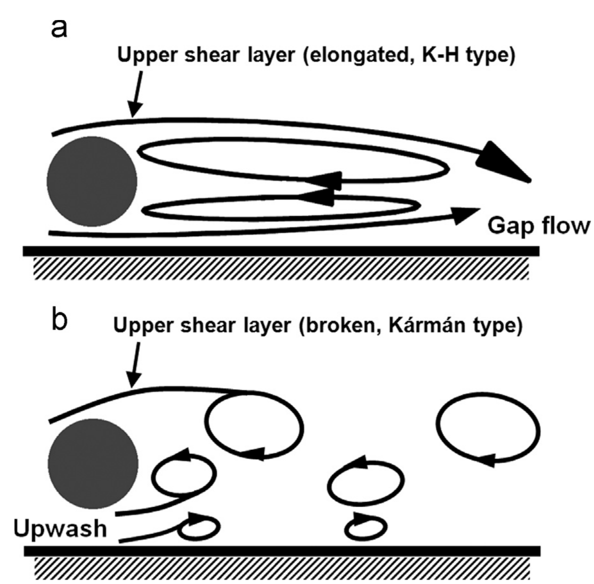


**Fig. 2.** Schematic of the flow around a near-wall single cylinder: (a) vortex-shedding-suppression regime at small gap ratio; and (b) vortex-shedding regime at moderate gap ratio. Proposed based on the flow measurement results in Wang and Tan (2008a).

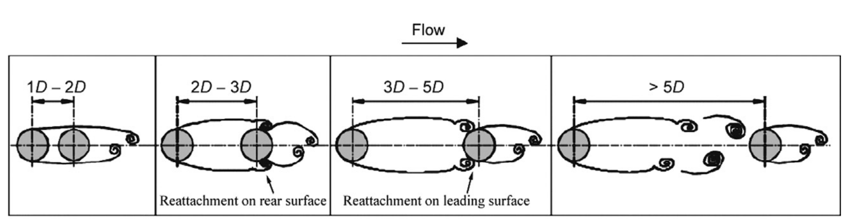


**Fig. 1.** Schematic of the flow around two tandem cylinders as a function of spacing ratio ($L^*$) under free-standing conditions. Modified from Zhou and Yiu (2006).