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Wake of tandem cylinders near a wall

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ABSTRACT

This article reports an experimental investigation on the near wake of two identical circular cylinders in crossflow arranged in tandem configuration in the streamwise direction and with the additional interference of the ground. The Reynolds number based on the cylinders diameter is 4.9×10^3. The present study analyses the effect of longitudinal pitch-to-diameter ratios spanning the well known flow regimes of tandem cylinders in absence of ground effect, i.e. single bluff body, shear layer reattachment and vortex co-shedding of twin cylinders. Particle Image Velocimetry measurements are performed to extract first and second order statistics of the wake. The wake features have been analyzed and compared with the bluff-body wake models present in literature. Additionally, the flow fields are decomposed in Proper Orthogonal modes to characterize the main coherent structures. The time coefficients of the modes are analyzed to extract phase relations between vortical features.

Far enough from the wall the cylinders wake is symmetric, with Von Kármán vortices shed symmetrically in the wake with respect to cylinders centerline. The measured average wake characteristics and vortical structures are consistent with the data reported in the literature for tandem cylinders without ground effect. For a wall-to-cylinder gap equal to 1 diameter, the ground strongly influences the flow field, introducing asymmetry in the typical Von Kármán wake. The ground boundary layer is thickened past the downstream cylinder and a wall-jet appears, enclosed between the wall boundary layer and the cylinders wake. Eventually these flow structures are not distinguishable when the cylinders wake and the wall boundary layer are grown enough to merge. From POD analysis, vorticity blobs appear on the wall, paired with vortex shedding.

If the wall gap is decreased to 0.3 diameters, an extended low speed region appears close downstream of the cylinders. A POD mode similar to a vortex shedding is still present; however it cannot be associated to an alternate Von Kármán street. The shed structures show a shorter wavelength than the Von Kármán shedding in far-from-the ground cases and are accompanied by a flapping jet-like structure ejected from the wall gap between the cylinder and the wall. The jet strongly changes the features of the wake on the side opposite to that of the wall, thus suggesting a possible coexistence between jet oscillations and shedding.

1. Introduction

The periodic flow behavior generated by a cylinder or by a bluff-body in general, immersed in a cross flow has been widely studied [1]. The formation of periodic shedding of counter rotating vortices, known as Von Kármán vortices, gives rise to fluctuating forces and noise. The shedding occurs at a Strouhal number based on the cylinder diameter ($St = fD/V$ where f is the shedding frequency, D is the cylinder diameter and V is the free stream velocity) equal to about 0.2 in a range of Reynolds number $1300 < Re < 5000$ [2]. In this range of Reynolds numbers the shedding generally occurs with a laminar boundary layer, while transition to turbulent wake occurs further downstream with respect to the separation points.

The flow around arrays of cylinders immersed in a cross-flow is a typical engineering problem that can be found in many applications. Cylinder-like structures are typical elements, for example, of heat exchangers, cooling systems for nuclear power plants, off-shore structures, buildings, chimneys, powerlines, struts, grids, screens, and cables. Often these structures work in close proximity, thus introducing strong interaction effects between their respective wakes, thus affecting both amplitude and frequency of the periodic flow oscillations. Similarly, ground-structure interaction can effectively modify the behavior of the flow surrounding these objects such as in the case of underwater pipelines or arrays of

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bluff-bodies in ground effect. Understanding the behavior of tandem cylinders in ground effect is of paramount importance to design structures immersed in their wake and that are subjected to unsteady loads.

The flow around two cylinders in tandem configuration has been widely studied by [3,4]. A complete review of the subject is given by [5]. Depending on the Reynolds number and on the center-to-center longitudinal pitch (expressed in non dimensional form as L/D, abbreviated hereafter as the longitudinal pitch ratio) three main flow behaviors can be identified. At small longitudinal pitch ratios (approximately $1 < L/D < 1.2$–1.8 according to [4], or $1 < L/D < 2$ according to [6], depending on the Re range) the Kármán vortex shedding for the upstream cylinder is completely suppressed and the two cylinders act as a single bluff-body. Meneghini et al. [7] observed that vortex roll-up occurs closer to the downstream cylinder with respect to the single cylinder case. This flow regime has been often defined as *extended-body* or *single bluff-body regime* as sketched in Fig. 1a. At intermediate longitudinal pitch ratios (approximately 1.2–$1.8 < L/D < 3.4$–3.8 according to [4] or $2 < L/D < 5$ according to [6], depending on the range of Re) a complex flow behavior appears in the space between the cylinders. Even if in this regime the flow can show different behaviors, it can be mostly characterized by the reattachment of the separated free shear layers from the upstream cylinder on the surface of the downstream cylinder. This regime is referred as *reattachment regime* as sketched in Fig. 1b. At larger longitudinal pitch ratios (approximately $L/D < 3.4$–3.8 according to [4] or $L/D < 5$ according to [6], depending on the range of Re) both the cylinders develop a wake with the typical features of a Kármán street. This regime, sketched in Fig. 1c, is referred as *co-shedding regime*. In the co-shedding regime, both the cylinders shed vortices at the same frequency, with the upstream cylinder shedding triggering the downstream one (see [8]). The vortices shed from the downstream cylinder are larger in size but weaker in intensity than in the previous regimes [6].

The different regimes for various L/D are characterized also by the variation of the shedding frequency of the Von Kármán vortices in the cylinder wake; in particular Xu and Zhou [9] characterized the variation of the corresponding Strouhal number spanning through the tandem-cylinders regimes. For small longitudinal pitch-to-diameter ratios the Strouhal number is higher than 0.2 (shedding occurs at higher frequency than for an isolated cylinder). For higher longitudinal pitch ratios, the Strouhal number decreases, reaching values lower than 0.2 in the reattachment regime. A discontinuous jump occurs when the flow behavior passes from the *reattachment* to the *co-shedding regime*. For higher longitudinal pitch ratios the Strouhal number slowly approaches 0.2.

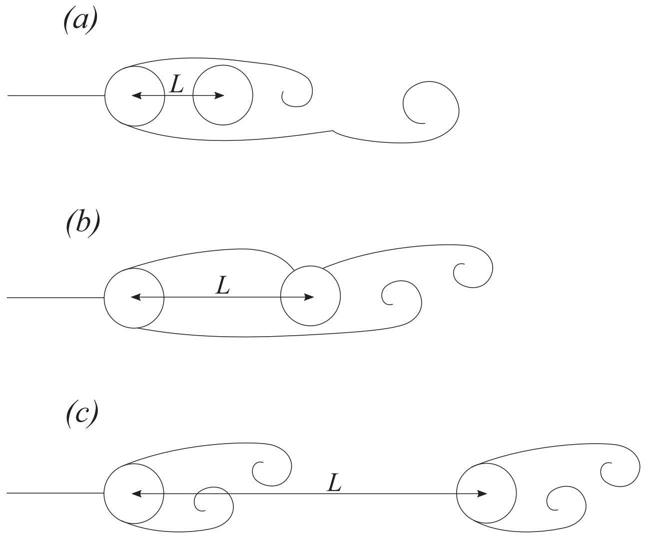

Fig. 1. Flow behaviors for cylinders in tandem configurations: (a) bluff-body regime, (b) reattachment regime, and (c) co-shedding regime.

The effect of the ground proximity has been investigated for both circular e.g. [10–12] and square see [13–16] single cylinders. The ground affects the pressure distributions, as well as the flow-induced vibration modes. The interaction of the cylinder with the wall has been also demonstrated to be a useful mean to control the flow in more complex arrangements e.g. [17]. The flow behavior is controlled by the ratio between the cylinder-to-wall gap height and the cylinder diameter (G/D, abbreviated hereafter as the wall gap ratio). According to [18] a critical wall gap ratio between 0.3 and 0.5 the Von Kármán vortex shedding is suppressed as the wall poses an irrotational constraint on the cylinder wake. According to [11], however, periodical release of vorticity is still present and its frequency depends on the Reynolds number for $Re < 2000$. Lin et al. [19] found evidence of the presence of a wall-jet flowing from the wall gap for wall gap ratios lower than 0.3, showing that this jet presents a self-similar velocity profile.

Little attention has been paid to the effect of the wall proximity in the case of two cylinders in tandem configuration. Bhattacharyya and Dhinakaran [20] investigated with 2D simulations the flow around two near-wall tandem square cylinders ($G/D = 0.5$, $L/D = 1.5$–6, $Re = 100$–200) with a shear velocity profile imposed upstream of them, and found that the cylinders wake resulted in a non-symmetric flow behavior: both non-uniformity of the flow and wall-induced vorticity weakens the lower separated shear layer with respect to the upper one. Harichandan and Roy [21] simulated the flow around two near-wall tandem circular cylinders ($G/D = 0.5$–1, $L/D = 2$–5, $Re = 100$–200): for $L/D = 5$ the shedding frequencies of both upstream and downstream cylinders are found to be equal. Moreover, the wake of tandem cylinders is less effective than the wake of a single cylinder in destabilizing the downstream wall boundary layer and causing separation. Wang et al. [22] measured with PIV the flow field around two square cylinders at $Re = 6300$ spanning a wide parametric space in both longitudinal pitch ratio ($L/D = 1.5$–7) and wall gap ratio ($G/D = 0.25$–2). Similarly to the case of the single cylinder for wall gap ratios below 0.5 the shedding is found to be suppressed. The interaction with the wall boundary layer is found to be relevant up to $G/D = 1$.

This work focuses on the near wake mechanisms downstream of tandem circular cylinders in ground effect. The flow field is measured by means of Particle Image Velocimetry (PIV, [23]) and reduced in principal components with Proper Orthogonal Decomposition (POD, [24]) to extract the dominant coherent structures. In particular this work uses the statistical information of POD to clarify how the shedding mechanisms are influenced by the multiple cylinders/wall interactions and whether (and how) shedding is suppressed for small wall gaps between the cylinder and the wall. In Section 2 the experimental setup and the test conditions are described. The data collected from each experiment are used to calculate first and second order statistics; the results are presented in Section 3 along with POD modes and are discussed and synthesized in Section 4.

2. Experimental methodology and processing techniques

2.1. Experimental setup and test procedure

The experimental setup is similar to that in [25]. The experimental study has been carried out in the closed loop wind tunnel