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Flow patterns and turbulence effects in large cylinder arrays

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ABSTRACT

Studies on flow-induced vibrations in large tube bundles are usually focused solely on frequency analysis, without considering the flow patterns which are responsible for the fluid forces. Furthermore, investigations which involve variations in the spacing ratios do not separate transversal and longitudinal proximity effects. The purpose of this article is to separately analyze the influence of the transversal (T/D) and longitudinal (L/D) spacing ratios of a confined in-line cylinder array with five rows on the flow characteristics and to identify flow patterns. The laser Doppler anemometry technique was employed to acquire the mean velocity and its fluctuations in the transversal and longitudinal directions between the cylinder rows. Strouhal numbers and regimes reported in the literature were identified in the experiments. The same regime did not always persist along all cylinder rows for a given spacing ratio, as a result of the combined longitudinal and transversal proximity effects and also of the generation of turbulence by the array. For the smallest T/D ratio, a quasi-steady behavior associated with the biased flow pattern was noted in the experimental set-up and flip-flopping was observed in one case. Additionally, the flow characteristics in these arrays diverged from tube bundle classifications described in the literature. The behavior of the fluid forces and susceptibility to vibrations in the array were predicted based on the turbulence intensity of the incident flow of the cylinders. The results reinforced the need to extend flow pattern investigations to arrays with more cylinder rows and to consider both transversal and longitudinal proximity effects, when studying flow-induced vibrations.

1. Introduction

Flow-induced vibrations are present in all industrial turbulent flows, internal or external to solid structures, due to the transient nature of fluid forces. This issue can become problematic, especially concerning the cross-flow around cylinder arrays, found in many types of engineering infrastructure, such as marine petroleum risers and offshore structures, tubular heat exchangers, chimneys and nuclear reactors. Vibrations can cause noise, fatigue in tube supports and, in the most severe cases, the rupture of tubes. Industrial cases of material and financial damage due to flow-induced vibrations have been reported by Païdoussis (2006) and Silva et al. (2016a).

These vibrations occur due to periodic forces that arise from flow separation and the shedding of vortices from the cylinders. The cross-flow past a single cylinder as well as its relation to fluid forces and the Strouhal number have been extensively studied and are well documented (Williamson, 1996; Sumer and Fredsøe, 1997; Norberg, 2003). The Strouhal number is defined as $\mathrm{St} = f_v D/U_\infty$, where f_v is the vortex shedding frequency, U_∞ is the flow velocity and D is the cylinder diameter. The flow around cylinder arrays, however, is more complicated due to the interference effects of adjacent cylinders. In recent decades, the number of published articles related to two parallel cylinders in cross-flow – which is the smallest parcel of an array – has increased significantly, as discussed by Zhou and Alam (2016). Recent reviews by Sumner (2010) and Zhou and Alam (2016) addressed flow structure and classification, fluid forces, Strouhal number and Reynolds number effects for two cylinders in cross-flow arranged at various pitch ratios (distance between the cylinders centers divided by their diameter, P/D) and angles of incidence α, which is the angle between the flow and the line connecting the centers of the cylinders. For two cylinders arranged side-by-side ($\alpha = 90°$), the transversal pitch ratio will be referred to as T/D, and for two cylinders arranged in tandem ($\alpha = 0°$), the longitudinal pitch ratio will be referred to as L/D.

As mentioned by Lam et al. (2003a), fluctuating forces and the Strouhal number for cylinder arrays are a consequence of the flow patterns, so the understanding of the flow is key to preventing vibrations. Sumner (2010) highlights three main flow patterns for the tandem configuration: the single bluff-body flow ($\frac{L}{D} < 1.2 \sim 2$), shear layer reattachment regime ($1.2 \sim 2 < L/D < 3.4 \sim 5$) and vortex shedding from both cylinders, or co-shedding pattern ($L/D > 3.4 \sim 5$). For the side-by-side arrangement, the major flow patterns reported by Sumner (2010) are the single bluff-body flow ($T/D < 1.1 \sim 1.2$),

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biased vortex streets ($1.1 \sim 1.2 < T/D < 2 \sim 2.2$) and parallel vortex streets ($T/D > 2 \sim 2.2$).

For two cylinders in a staggered arrangement, different approaches have been taken for flow pattern classification, as reported by Zhou and Alam (2016). One of these was proposed by Sumner et al. (2000), who identified wake interaction regimes according to the angle of incidence α. For small pitch ratios, two types of single bluff body flow are described depending on α, along with the base-bleed pattern with a weak gap flow biased toward one of the cylinders. The small incidence angle patterns observed include the shear layer reattachment flow pattern, the induced separation on the inner surface of the downstream cylinder caused by the inner shear layer of the upstream cylinder, and the vortex impingement flow pattern. For larger incidence angles, Sumner et al. (2000) report the pairing of gap vortices and their enveloping by a vortex shed from the outer shear layer of the upstream cylinder, the vortex pairing, splitting and enveloping flow pattern, and synchronized vortex shedding from both cylinders in anti-phase.

The transition from one flow pattern to another is mostly discontinuous, with an intermittent change between two states. This is known as bistable flow and it can lead to additional instabilities as it modifies the dynamical response of the cylinders (Olinto et al., 2009). For two cylinders in tandem, the bistable flow manifests in the coexistence of the shear layer reattachment and co-shedding regimes at a critical pitch ratio that is dependent on the Reynolds number (Alam et al., 2003a; Elhimer et al., 2016). Two cylinders side-by-side under the biased vortex streets flow pattern may present spontaneous switching of the cylinder to which the wakes are biased, also known as the "flip-flopping" regime (Alam et al., 2003b; Wang and Zhou, 2005). The switch can also occur due to stopping and restarting the flow or by causing a large perturbation, a behavior termed "quasi-stable" by Guillaume and LaRue (1999). Four types of bistable flow were identified by Alam et al. (2005) for two staggered cylinders, related either to the intermittent reattachment of one of the shear layers, the formation and burst of a separation bubble on the inner surface of one of the cylinders, or the switch between a narrower and a developed Karman wake behind the upstream cylinder. The combination of these phenomena also results in tristable and quadristable flows (Zhou and Alam, 2016).

Several investigations have been carried out on the flow characteristics and fluid forces of a four-cylinder array in a square-shaped configuration. Wang et al. (2013) reviewed published articles on this subject and performed additional experiments at $Re_D = 8000$ using particle image velocimetry (PIV) and taking force measurements at different spacing ratios and angles of incidence. For the in-line configuration ($\alpha = 0°$), flow regimes similar to those described by Sumner (2010) were observed. As α increased, the vortex shedding mechanism was intensified. For the diamond configuration ($\alpha = 45°$), Wang et al. (2013) highlighted the formation of high velocity jets between the upstream cylinder and its flanking neighbors at smaller pitch ratios. For spacing ratios higher than 3, flow interference decreased and the wakes were comparable to that of a single cylinder.

Lam et al. (2003b) carried out a similar investigation with $P/D = 4$ and $Re_D = 200$, for different angles of incidence, and the patterns observed differed from those described for two staggered cylinders. The vortex impingement and jet flow regimes were identified as the most concerning in relation to flow-induced vibrations. This observation was confirmed by the force coefficient and Strouhal number measurements at variable spacing ratios and incidence angles with Re_D between 2.25×10^4 and 4.5×10^4 (Lam et al., 2003a).

Large tube bundles were classified by Ziada and Oengören (1993) into small, intermediate and large tube spacings. For in-line arrays in the subcritical regime ($300 < Re_D < 3 \times 10^5$), the arrays are characterized by the predominant flow instabilities, which can generate periodic flow excitations: closely-spaced arrays ($L/D < 1.5$) present weak jet instabilities in the flow lanes, in a symmetric mode and only in the upstream rows of the array, causing small vortices. Moderately-spaced arrays ($1.75 < L/D < 2.7$) were found to feature jet instabilities along all rows of the tube bundle, symmetric in the flow lanes but antisymmetric in the wakes due to the formation of larger vortices. Vortex shedding in widely-spaced arrays ($L/D > 2.7$) may be governed either by global symmetric instability of the jets or by local wake instability in the first rows of the array, depending on the upstream turbulence intensity of the flow (Ziada et al., 1989; Ziada and Oengören, 1992, 1993). This classification is limited, however, to the streamwise spacing ratio L/D.

Other studies on large arrays have been carried out by Paul et al. (2007, 2008), who performed PIV measurements in a section with twelve tubes arranged in a staggered array. Lam et al. (2010) obtained velocity profiles with the laser Doppler anemometry (LDA) technique and force measurements for a staggered array of fourteen cylinders to validate a large eddy simulation model. Mahon and Meskell (2012) measured the surface pressure on a cylinder in the sixth row of a staggered array with $P/D = 1.375$ as well as fluid forces, focusing on fluidelastic instability. The biased and bistable flow reported for two side-by-side cylinders was shown to occur also for cylinder arrays. Olinto et al. (2006, 2009) identified this pattern by means of the wavelet transform of hot wire anemometry measurements in the first rows of an in-line square tube bundle with different pitch ratios. De Paula et al. (2012) similarly studied the bistable flow for a staggered array, describing a "jet switching" behavior, which was also identified in experiments by Mahon and Meskell (2012). Keogh and Meskell (2015) performed a more in-depth investigation of the bistable flow in a rotated triangular array with $P/D = 1.375$ through PIV and pressure measurements.

As stated previously, the flow around cylinder arrays is more complex than around a single cylinder and it is dependent on the array configuration and cylinder spacing ratios. It can be noted that in-depth investigations on flow characteristics and cylinder proximity effects are mostly concentrated on arrays of up to four cylinders. In general, previous studies involving large cylinder arrays focused on a single configuration each, and in investigations with different spacing ratios only the Strouhal behavior was analyzed.

There is still a lack of understanding regarding the factors influencing whether or not the flow regimes identified for two or four cylinders are reproduced in larger arrays. The aim of this study was to partially fill this gap in the literature by investigating the flow behavior in an in-line array of up to 25 cylinders at a turbulent Reynolds number. The separate influence of the transversal and longitudinal spacing ratios on the flow behavior has not yet been addressed in the reviewed literature. Therefore, as an original contribution to this subject, the influence of T/D and L/D was evaluated with two levels of each spacing ratio combined to generate four different cylinder arrays for the analysis. Experimental measurements using LDA were performed at $Re_D = 1200$, calculated based on the average flow velocity in the test section and on the cylinder diameter.

2. Experimental details

Experiments were conducted at atmospheric pressure and temperatures around 25 °C in a closed-circuit water channel, as shown in Fig. 1a. The channel is 1 m long and built of acrylic, with a width of 8 cm and maximum height of 20 cm. A segmented lid can be placed over the channel at the water level to avoid the formation of a free surface, thereby allowing greater confidence in the flow rate values, in addition to granting a reliable boundary condition in subsequent computational fluid dynamics (CFD) simulations. The lid is segmented so its middle section can be replaced with different perforated plates, enabling the cylinder insertion according to the desired array configuration. Polyacetal rods with 1 cm of diameter are used to model the cylinders, and are additionally supported in place by a second perforated plate on top of the channel.

To separately evaluate the influence of the spacing ratios in the