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Short communication

Impact of the downstream cylinder displacement speed on the hysteresis limits in a flow around two rectangular objects in tandem – PIV study of the process

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ABSTRACT

This paper is about experimental study of air flow around two identical square cylinders arranged in tandem with the use of particle image velocimetry approach. Impact of progressive increase and progressive decrease in the spacing between centres of the cylinders (ranging from 2 to 9 widths of the cylinder) on a hysteresis limit were investigated. The hysteresis is associated with two discontinuous jumps in the flow patterns and occurs when the spacing between cylinders varies in two ways. Particular attention was devoted to the study of the downstream cylinder displacement velocity (ranging from 0.01 to 0.09 m/s) on the hysteresis range for different free-stream Reynolds numbers (Re = 4100–32940). The changes in the flow pattern were determined based on the time histories of velocity fluctuations analysed independently in the most characteristic regions of the measuring section. The impact of the downstream cylinder velocity and the Reynolds number on the lower and the upper spacing limits of the hysteresis was presented and discussed.

1. Introduction

Fluid flow around bluff bodies has been an object of considerable research as this issue is of huge fundamental and practical value. The basic example of such process is the case when the flow passes over a single rectangular cylinder and this issue is well described in the literature. A number of works dedicated to different fundamental aspects can be found in the available literature. These include studies on: impact of turbulence intensity on cylinder surface pressure (Lee, 1975); Strouhal number (Okajima, 1982); different incidence angles of the cylinder with respect to the flow (Chen and Liu, 1999; Huang et al., 2010; Sohankar et al., 1998); flow behaviour at low (Saha, 2013; Saha et al., 2003) and high (Larose and D'Auteuil, 2008) Reynolds numbers; different corners' shapes of the cylinders (Tamura et al., 1998; Tamura and Miyagi, 1999), fluid–structure interactions (Miyanawala and Jaiman, 2018).

A more complex case is when two square cylinders are in the tandem (or in-line) arrangement, i.e. when one cylinder is immersed in the wake of another. This is due to the flow interference, occurring in the short gap between them. It plays an essential role in a number of engineering applications (flow around buildings, heat exchangers or electronic devices may serve as examples). It is also commonly known that the flow pattern, in particular, in the region between these two objects strongly depends on the distance between the cylinders' centres (denoted hereafter as L). When exceeding a so-called critical spacing the flow behaviour instantly changes. When the inter-cylinder spacing is smaller than the critical one vortices sheading from the upstream cylinder elude the gap between prisms and reach the side walls of the downstream cylinder. Such a flow behaviour is called in literature as *Mode I*. When the spacing between cylinders is larger than the critical one vortices shedding from the upstream cylinder enter the gap between the structures leading in turn to abrupt increase in drag acting on them. This flow pattern is commonly known as *Mode II*. The other feature characteristic for such objects' configuration is a presence of hysteresis with two discontinuous jumps in aerodynamic characteristics. The hysteresis appears when increasing and

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then decreasing the spacing between cylinders (in both directions the critical spacing must be exceeded).

This issue has been the object of extensive research for the last thirty years. In one of the earlier studies, Sakamoto et al. (1987) investigated experimentally a flow around two square cylinders for different spacing ratios L/D, where D is the width of the cylinder. It was found that for the Reynolds numbers $Re_D = 27600$ and 55200 the critical spacing remained the same, i.e. $L/D = 4.0$. Authors also observed a synchronisation of vortices shedding from both cylinders until the spacing was increased up to $L/D = 28$. For $L/D > 28$ shedding frequency of vortices was found to be individual for each square cylinder. The same critical spacing value, i.e. $L/D = 4.0$, was found by Luo and Teng (1990) for $Re = 56700$. Ljungkrona et al. (1991) investigated an impact of different turbulence intensities on critical spacing under the Re = 20000. It was discovered that with increasing turbulence intensity, from 0.1 to 3.2%, the critical spacing decreased from 3.5 to 2.5. Liu and Chen (2002) analysed the flow over two square cylinders in the tandem arrangement when the gap spacing was progressively increased from $L/D = 1.5$ to 9.0 and then progressively decreased from $L/D = 9.0$ to 1.5. Such an experimental procedure allowed to observe a presence of hysteresis with two discontinuous jumps in aerodynamic characteristics such as lift and drag coefficients and Strouhal number. Each discontinuity was associated with a sudden change in the flow pattern. During the progressive increase in the gap spacing the change from *Mode I* to *Mode II* occurs and vice-versa. The authors analysed much smaller Reynolds numbers than these previously reported in the literature, namely $Re = 2000$ to 16000. However, the studies revealed that the hysteresis regime shifts towards the lower values of spacing with increasing Reynolds number up to $Re = 5300$ and then remains almost unchanged for higher values of Re. Worthy of note is also that the authors pointed out that the speed of the cylinder displacement might influence the jump between two flow patterns, however, this issue was not investigated. Even smaller Reynolds numbers, $Re = 40$–1000, were analysed in computational fluid dynamics (CFD) simulations performed by Sohankar (2012). Author found that presence of the hysteresis is caused not only due to a continuous change in the gap spacing but also due to a continuous change in the Reynolds number. It was presented that the hysteresis limits are in the range $L/D = 2.75$–4.75 for $Re = 130$, 150 and $L/D = 2.25$–4.75 for $Re = 500$. In the other work of Sohankar (2014) large eddy simulation approach was used to study the interference effects of the tandem square cylinders exposed to a uniform airflow. A series of 3D - CFD simulations were performed for selected Reynolds numbers ranging from 1000 to 100000 and spacing between cylinders from $L/D = 1$ to 12. It was found that the hysteresis limits are in range of $L/D = 2.25$–3.25 for $Re_D = 2700$ and 1.5–2.5 for $Re_D = 20000$. Flow visualisations allowed to report various vertical structures, in particular Kelvin–Helmholtz (KH) vortices in the separating shear layers of the upstream cylinder. Nikfarjam and Sohankar (2015) studied the hysteresis associated with non-Newtonian fluids passing square cylinders in tandem. The results indicated much wider hysteresis range for power-law fluids than for Newtonian ones. For instance, at $Re = 100$ and for power-law index $n = 0.7$ the hysteresis occurs for $L/D = 2.0$–7.0, however, with increasing power-law index the hysteresis limit diminishes. Worthy mentioning is also the paper of Yen et al. (2008). Authors immersed two square cylinders in tandem inside a vertical water tank and investigated, using PIV approach, the effects of the Reynolds number, the spacing limit and the rotational angle of downstream cylinder on flow pattern. When changing the Reynolds number and the spacing limit, three characteristic modes were identified, i.e. vortex sheet of the single mode, reattached mode and binary mode. In addition, when changing the spacing limits and the rotation angles of the downstream cylinder the flow field was categorised into six modes.

Similar studies can be also found for circular cylinders in tandem. Wang et al. (2010) analysed numerically a secondary vortex street in the wake of two circular cylinders arranged in line. Authors observed the presence of hysteresis characterised in sudden change in Strouhal ranging from about L/D = 4 to 5 for Re = 60 up to about $L/D = 3.5$ to 4.6 for $Re_D = 100$. Liu et al. (2014) re-examined the impact of increasing L/D ratio (from 1.1 to 7) on aerodynamic characteristics for $Re_D = 200$. A sudden increase at $L/D = 3.6$ in flow properties were observed. It is worthy to note that in both works (Liu et al., 2014; Wang et al., 2010) authors also observed a sudden decrease in Strouhal number at $L/D \approx 1.9$. Tasaka and Kon (Tasaka et al., 2006) showed that the presence of the hysteresis (for two circular cylinders in tandem) can be achieved when progressively increasing and then progressively decreasing Reynolds number (within the range between $Re_D = 100$ and 300), however, only for the spacing limit $L/D = 4.6$ to 5.

There has also been a growing body of research focusing on practical application of the knowledge related to the flow passing through two square cylinders in the tandem arrangement. Inoue et al. (2006) analysed numerically the sound waves generated by the flow past two square cylinders. It was found that with increasing spacing beyond a critical value a drastic jump in the magnitude of the generated sound occurs. Patil and co-workers (Patil et al., 2008) investigated forced convection heat transfer characteristics of the power-law fluids passing over a pair of cylinders in tandem. The results revealed that for the gap spacing ratios beyond the critical value the Nusselt number for the upstream cylinder is comparable to this for the downstream one. Also other works related to similar studies (Chatterjee and Mondal, 2012; Nikfarjam and Sohankar, 2015) confirmed that *Mode I* impedes the heat transport whereas the *Mode II* facilitates it. When analysing the flow around two buildings in tandem the flow pattern corresponding to the *Mode II* may lead to accumulation of pollutants in the gap between them and may also have an adverse impact on pedestrians walking around. More details about airflow passing two buildings arranged in tandem can be found in the following publications (Błazik-Borowa et al., 2011; Gnatowska, 2015, 2011; Gnatowska and Moryń-Kucharczyk, 2010; Gnatowska et al., 2017).

The purpose of the present work is to analyse the impact of the downstream cylinder displacement speed on the hysteresis in a flow around two rectangular objects in tandem. Detailed insight into the flow pattern was gained by adopting a particle image velocimetry (PIV) technique. The investigation was performed for wide range of Reynolds numbers (4100–32940) and displacement velocities of the downstream cylinder (0.01–0.09 m/s). In turn, the hysteresis limit was determined as a function of all analysed parameters. Primary motivation for this research is to address the hypothesis formulated by Liu and Chen (2002) saying that the speed of the downstream cylinder displacement might influence the hysteresis limit. To the best of authors' knowledge there is no journal paper verifying this statement and hence, this work is aimed at filling this gap.

2. Experimental procedure

Measurements were performed using the experimental setup which general scheme is presented in Fig. 1. It consisted of horizontal, closed circuit, low speed wind tunnel and the PIV system with 5.5 Mpx sCMOS camera. Flow was seeded with ~1 μm droplets of Di-Ethyl-Hexyl-Sebacate (DEHS). Illumination was provided by a double cavity laser adjusted on the second harmonic (wavelength of 532 nm) emitting a pair of pulses with energy of 0.2 J each and with a frequency rate of 15 Hz. Along the longitudinal axis of the wind tunnel bottom wall a low profile linear roller guide was mounted.

The upstream cylinder was firmly fixed close to the beginning of the linear roller guide. The downstream cylinder was fixed to the trolley which was operated remotely and was able to start rapidly and then move with a constant velocity. Both cylinders where made of aluminium square pipes filled with a heavy input to increase their stability and to avoid vibrations. Cylinders were tall enough to reach the boundary layer at the upper wall, however, a small technical gap had to be kept. The experiment was preceded by smoke visualisation tests aimed at identifying the impact of the roller guide on the airflow within the domain. A slight airflow disturbances appearing in the closest vicinity of the linear roller guide were observed, however not affecting the measuring section.