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Stability of Flow around Two Rectangular Cylinders in Tandem

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The experimental study with the use of particle image velocimetry (PIV) has been conducted to investigate the stability of flow around two identical square cylinders in tandem arrangement at a different Reynolds numbers. The important study parameter was the displacement of the downstream cylinder with velocity in range from $V_c = 0.01$ to 0.09 m/s. Effect of gradually increasing and decreasing the spacing between the cylinders, in the inter-cylinder spacing ratio from 2 to 9, on a stability of flow was investigated. The unstable flow is connected with two discontinuous jumps in the flow patterns and occurs when the spacing between cylinders varies in two ways. The changes in the flow modes were determined based on the time histories of velocity fluctuations analysed independently in number of points located in different 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 unstable modes was presented and discussed. The results show that the unstable flow modes are highly dependent on the combined values of free-stream Reynolds numbers Re_D and the downstream cylinder displacement velocity V_c.

topics: square cylinders, tandem arrangement, PIV, fluid flow, vortex shedding

1. Introduction

Multi-cylinders structures can be found in many engineering applications, for example: heat and cooling exchangers, systems for nuclear power plants, offshore structures and cables, in both air and water flow. The available literature provides an interesting insight into the basic aspects of flow around rectangular cylinders [1–7]. The topic is interesting and there are papers dedicated to the more complex case when two square cylinders are in the tandem (or in-line) arrangement, i.e., when one cylinder is immersed in the wake of another. In the earlier studies, Sakamoto et al. [8] and Luo et al. [9] investigated experimentally a flow around two square cylinders for different spacing ratios L/D, where L is the distance between the cylinders' centres, D is the width of the cylinder. Authors were found the critical space for which the flow behaviour instantly changes ($L/D = 4.0$). When the inter-cylinder spacing is smaller than the critical one vortices sheading from the upstream cylinder escape the gap between cylinders and reach the side walls of the downstream cylinder (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 (Mode II). Liu and Chen [10] analysed the flow over two square cylinders in the tandem arrangement when the gap spacing was progressively increased and decreased in range $L/D = 1.5$ to 9.0. Such 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 from Mode I to Mode II, and vice-versa. Although the studies revealed the hysteresis regime shifts for different Reynolds number and the speed of the cylinder displacement, however, this issue was not investigated.

The growing number of studies are focused on practical application of the knowledge of the flow around two square cylinders. Inoue et al. [11] analysed numerically the sound waves generated by the flow past two cylinders. Cekus et al. [12] consider the effect of wind influence on the movement of the cubical load during the working cycle. During the test the stability of motion and prevent vibrations were analysed. Chatterjee and Mondal [13] and Nikfarjam and Sohankar [14] 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. More details about flow around two buildings arranged in tandem can be found in the following publications [15–17].

The purpose of the present work is to analyse the unstable flow occurring when the spacing between cylinders in tandem varies in two ways, with the use experimental particle image velocimetry (PIV) technique. The investigation was carried for varied Reynolds numbers and displacement speed of the downstream cylinder. Motivation for these went from the research presented by Sobczyk et al. [18] of the influence of downstream cylinder displacement speed on the hysteresis range for different free stream Reynolds numbers. To the best of authors' knowledge there is no journal paper describing physics of these unstable flow and hence, this work is aimed at filling this gap.

2. Experimental setup

Experiment was carried out in the closed circuit wind tunnel of Strata Mechanics Research Institute. Along the longitudinal axis on the wind tunnel measuring chamber bottom wall a low profile linear roller guide, with two aluminium squares, 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 move with a constant speed in two ways. Before the PIV experiment the smoke visualisation tests were made aimed confirmation of no impact of the roller guide on the airflow within the measuring section. Instantaneous flow fields were measured within area, marked on Fig. 1 with dotted line, laying in the plane going through centres of the cylinders. Measurements were performed under the following conditions: square cylinder width $D = 0.04$ m, measuring chamber dimensions $w \times h \times l = 0.5 \times 0.5 \times 1.5$ m^3, measuring area dimensions $w \times l = 0.17 \times 0.4$ m^2, free stream velocity: $1.55, 3.91, 7.99, 12.49$ m/s, and the corresponding free stream Reynolds numbers $\mathrm{Re}_D = 4100$, 10310, 21070, 32940, and the downstream cylinder movement speed $V_c = 0.01, 0.03, 0.06, 0.09$ m/s.

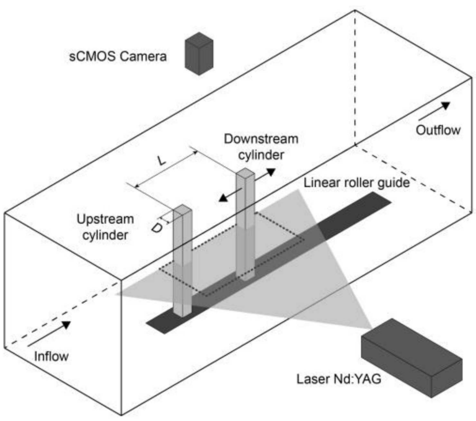

Fig. 1. Scheme of the experimental setup in wind tunnel [18].

The PIV system was managed by the Dantec software DynamicsStudio. The captivating of images is done by implementing a Nd-Yag laser 532 nm, with an impulse power of 2×200 mJ, camera of 2048×2048 px (Dantec FlowSense 4M) and the flow was seeded with < 1 μm oil droplets.

3. Experimental results

The aim of this experimental study is to obtain the detailed information about velocity field and interaction between objects in motion in tandem arrangement. Figure 2 illustrates the evolution of instantaneous vorticity fields when the spacing between cylinders was progressively increasing (a)–(c) and decreasing (d)–(f) the s for the case when the smallest Reynolds number and the highest downstream cylinder speed were considered, i.e., $\mathrm{Re}_D = 4100$ and $V_c = 0.09$ m/s. Figure 2a presents the initial configuration when the downstream cylinder do not move. As can be seen due to interaction between the front of the upstream cylinder and free stream flow in the wind tunnel a large vertical structure is generated. This structure avoids the gap between bluff bodies and sheds just behind the downstream cylinder and such a flow pattern corresponds to the Mode I.

When progressively increasing L/D the generated vertical structure is stretched, however, it still does not reach the region between cylinders (see Fig. 2b).

Further increase in the spacing leads to the change from Mode I to Mode II, i.e., when the large vortex structure enters the gap between cylinders (see Fig. 2c). When the distance between cylinders is progressively decreased with the same velocity V_c much smaller spacing must be reached for Mode I to arrive. Figure 2e illustrates the presence of Mode II when the downstream cylinder is moving back for much smaller L/D comparing to the situation shown in Fig. 2b where the Mode I is observed during the progressive increase in spacing. Hence, the presence of hysteresis related to change between Modes is evident. More details about characteristic of hysteresis can be found in the previous author's publication [18].

The detailed study of the time of velocity series allowed to know the physics of these unstable flow for different values of Re_D and V_c. The analysis was performed independently in the number of points located in different regions of the measuring section. The example results as the normalized transverse velocity component in time, are presented in Fig. 3. Investigation of all the recorded and processed data was led to the distinction of the three principal modes: Mode I, Mode II and Transient (unstable pattern) in many research points. It should be noted that this phenomenon was not clearly visible at all points. The duration time of this unstable mode was longer during the downstream cylinder going forth, than going back.

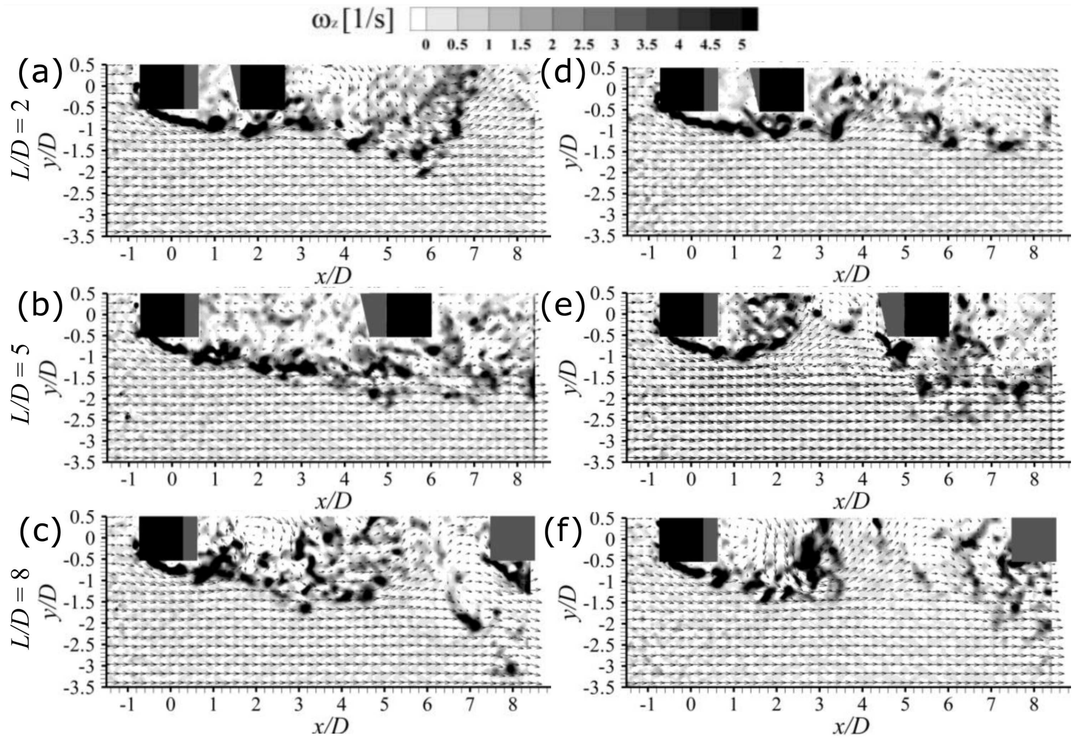

Fig. 2. Instantaneous vorticity fields with velocity vectors related to $\mathrm{Re}_D = 4100$ and $V_c = 0.09$ m/s, for increasing (a)–(c) and decreasing (d)–(f) distance between square cylinders.

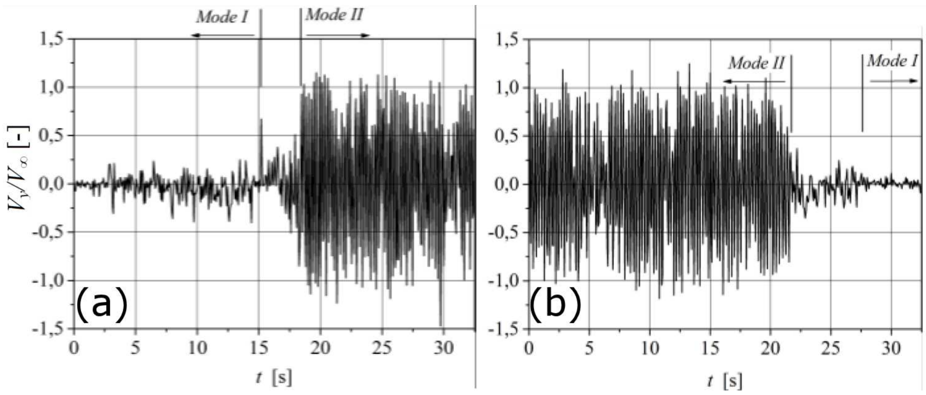

Fig. 3. The normalised transverse velocity in selected points when the spacing between cylinders was progressively increased (a) and decreased (b).

3. Conclusions

This experimental work investigates the flow phenomena appearing when progressive increase and decrease in spacing between two square cylinders in tandem takes place. Particular attention was devoted to the study of the downstream cylinder movement speed V_c on the flow stability for different free-stream Reynolds numbersRe_D.

The recognised Transient mode is associated with two discontinuous jumps in the flow patterns and occurs when the spacing between cylinders varies in two ways. Changes in the flow regimes were determined on the basis of the history of velocity fluctuations analysed independently in points located in different regions of the measuring section. The impact of the downstream cylinder displacement speed and the Reynolds number on the Transient mode was discussed. The results show that the flow regimes are highly dependent on the combined values of Re_D and V_c.

Acknowledgments

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