FLOW CLASSIFICATION AROUND TWO STAGGERED SQUARE CYLINDERS

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Abstract Flow around multiple slender structures has been the subject of intensive research because of its relevance to engineering structural design, flow-induced vibration and acoustic emission problems. Though circular and square sections are considered to be the basic shapes of structures, previous investigations are mostly focused on two circular cylinders [1, 2], which are the simplest configuration of multiple structures. There has not been much attention paid to the case of two square cylinders in close proximity of each other. While non-stationary flow separation point oscillates on a circular cylinder surface and it is highly dependent on the initial flow conditions (Reynolds number, turbulent intensity, etc.), flow separation from a square cylinder is fixed at the sharp edges. How this difference would impact on the flow around two cylinders has yet to be established. Recently, Alam et al. [3] observed many interesting flow physics in the wake of two side-by-side square cylinders, compared to circular cylinders. One can speculate that there might be interesting phenomena in the staggered case of two square cylinders and this intrigues the authors to conduct the present work. The objectives of the present study are to perform experimental measurements of dominant vortex shedding frequency (normalized to Strouhal number St), fluid forces and flow field in the wake of two square cylinders in staggered arrangement at a Reynolds number $Re = 1.4 \times 10^4$, based on the cylinder width d. The cylinder center-to-center pitch (P) ranges from $1.1d$ to $5d$ and the angle (α) between the line connecting cylinder centers and the incident flow is $0^o \sim 90^o$. Based on St behaviors, flow structure topologies, and their downstream evolutions, four distinct flow structures were identified at x^* (= x/d) ≥ 4 (where x is the downstream distance from the mid-point of the cylinder centers), i.e., two single-street modes (S-I and S-II) and two twin-street modes (T-I and T-II). Mode S-I, taking place at small α ($< 45^o$), was further divided into two sub-modes, S-Ia and S-Ib, in view of their distinct vortex strengths in the wake. Mode S-Ia occurred at P^* (= P/d) < 4.0 and $\alpha < 45^o$, where shear layers separating from the upstream cylinder either overshoot or reattach to the downstream cylinder, generating one staggered Karman vortex street. Mode S-Ib took place at large P^* (≥ 4.0) and small α ($< 20^o$), where vortices shed from both cylinders. Due to vortex impingement, vortex strength in mode S-Ib was greatly reduced compared with that in mode S-Ia. In mode S-II, both cylinders generated individual wakes, and vigorous interactions occurred between them in the near-wake region, producing one Karman vortex street at $x^* > 4.0$. This vortex street displayed distinct vortex shedding frequencies on opposite sides and, depending on from which cylinder the higher-frequency vortices were shed, mode S-II was categorized into two sub-modes, S-IIa and S-IIb. Higher-frequency vortices shedding from the downstream cylinder were observed at $x^* < 7.0$ in mode S-IIb, which occurred at $P^* = 1.5$ and $\alpha > 65^o$. By contrast, mode S-IIa took place largely at $P^* < 3.5$ and $\alpha > 45^o$, with higher-frequency vortices shedding from the upstream cylinder. Mode T-I was identified largely at $P^* \geq 3.0$ and $40^o < \alpha < 75^o$, characterized by two Karman vortex streets with slightly different vortex shedding frequencies. Mode T-II occurred largely at $P^* \geq 3.0$ and $\alpha > 75^o$ (sub-mode T-IIa), and at $P^* \geq 4.0$ and $20^o \leq \alpha < 40^o$ (sub-mode T-IIb). Mode T-IIa displayed two coupled Karman vortex streets, either anti-phased or in-phased, and mode T-IIb displayed two coupled Karman vortex streets that were anti-phased, because vortices shed from the inner side of the downstream cylinder were always synchronized with those from the inner side of the upstream cylinder. Vortex shedding frequencies in modes T-IIa and T-IIb were very similar to that of an isolated single cylinder. The dependence of flow modes on P^* and α is summarized in Figure 1, where thick lines indicate the border of the flow modes. Initial conditions connecting to different flow modes are discussed in detail.

Furthermore, as shown in Figure 1, time-averaged fluid forces (i.e. drag and lift) acting on the two cylinders were coherently associated with the flow modes. Low drag force acting on both cylinders and even negative drag force (opposite to the streamwise flow) on the downstream one were observed in mode S-Ia, because shear layers separating from the upstream cylinder enclosed the downstream one. However, in mode S-IIa the upstream cylinder suffered from high drag and positive lift forces (repelling the two cylinders from each other), resultant from the narrow wake associated with the cylinder. In mode S-IIb, the wide wake was produced by the upstream cylinder and thus low drag force was observed (Figure 1a). More interesting behaviors can be seen in the lift forces on both cylinders. For example, negative lift force (attracting the two cylinders by each other) was observed in the configurations where transitions took place from modes S-IIa to S-Ia, S-IIb, T-I and T-IIa. This is mainly ascribed to the behavior of gap flow between the two cylinders. In Figure 1(d), maximum positive lift force on the downstream cylinder was observed mainly at $\alpha = 20^o \sim 25^o$, irrespective of P^*; on the other hand, the downstream cylinder suffered from negative lift force in mode T-IIb. Flow physics, which may tightly connect to the fluid forces, were discussed in detail, based on measured flow structures in the wake.

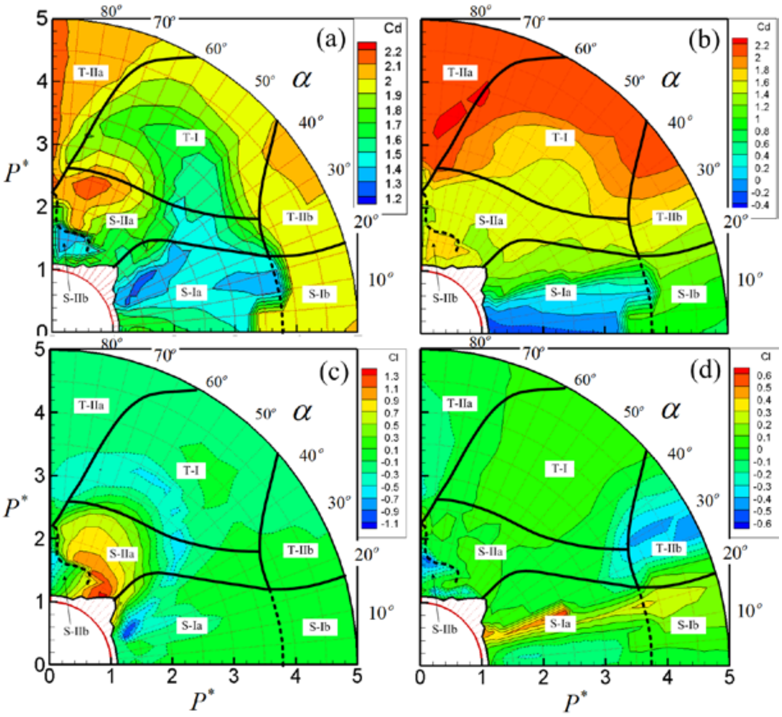

Figure 1. Dependence of flow modes on P^* and α in the wake of two staggered square cylinders at $Re = 1.4 \times 10^4$ [thick lines indicate the border of flow modes; iso-contours denote coefficients of time-averaged fluid forces acting on the two cylinders: drag force coefficient C_d on (a) the upstream cylinder and (b) the downstream cylinder, lift force coefficient C_l on (c) the upstream cylinder and (d) the downstream cylinder].

References

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