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Dynamic behavior of flow around rows of square cylinders kept in staggered arrangement

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ABSTRACT

A two-dimensional numerical study is carried out to understand the vortex dynamics behind two rows of square cylinders arranged in a staggered fashion in an unbounded medium and at low Reynolds number ($Re=100$). A uniform cross flow of an incompressible fluid is considered. The transverse spacing between the cylinders is varied ($S/d=1$, 2, 3 and 5; with S and d are the transverse spacing and cylinder size) while the streamwise gap is fixed at $L/d=1$ (L being the streamwise gap). Computations are performed by a finite volume based CFD solver using PISO algorithm. An unsteady two-dimensional laminar model is used for all the computations. Effect of transverse spacing on flow characteristics and global fluid dynamic parameters are discussed. Furthermore, the establishment of the low-dimensional chaotic nature of the flow is predicted for relatively small transverse spacing of the cylinders. The transition to chaos is manifested through a quasi-periodic route. The quasi-periodic route to chaos is established through different characterization tools, such as the spectra, autocorrelation function, time-delay reconstruction and the Poincare section. The chaotic behavior of the flow system is quantified through the calculation of the Lyapunov exponent and fractal dimension.

1. Introduction

The unsteady fluid flow around multiple bluff objects is of practical engineering importance and has attracted a considerable amount of interest in the recent past. Flow past a periodic array of bluff obstacles finds use in many engineering applications. In particular, offset-strip and louvered fin heat exchangers can be approximated as flow around a large periodic array of individual fin elements. Other applications can be found in porous media, fluidized beds, to mention but a few. Further, the study is of significant fundamental interest because of the fact that the wake interactions of multiple bluff bodies placed next to each others create a complex flow structure that results in a variety of unexpected phenomena. Examples are wake unsteadiness and onset of chaos even at small Reynolds numbers. Generally, the route to chaos is characterized by a critical Reynolds number. Here we show that the chaotic behavior is established for a small gap between the cylinders at $Re=100$ which is considerably smaller than the critical Reynolds number for the onset of transition to chaos for flow around a single square cylinder.

A number of experimental as well as numerical studies are available in the literature pertaining to the flow around row of circular cylinders. An extensive review in this regard can be found in Zdravkovich (1997, 2003), Chen (1987), Blevins (1990) and Sumner et al. (2000). However, a systematic study for the flow over a row of square cylinders is infrequent. The flow patterns and the wake structures for the case of flow over row of square cylinders are considerably different from the flow over row of circular cylinders because of the fact that unlike the circular cylinders the square cylinders fix the separation point, causing differences in the critical flow regimes. Furthermore, the separation mechanisms depending on the shedding frequencies and the aerodynamic forces also differ significantly for the two geometries. In the case of flow past a row of square cylinders, the nondimensional spacing (spacing to cylinder size ratio, S/d) and the Reynolds number (Re) are the two most important controlling parameters. Depending on these parameters, different wake patterns such as in-phase and antiphase synchronized pattern, non-synchronized pattern, flip-flopping pattern, single bluff body pattern and steady pattern can be observed. Price and Paidoussis (1984) obtained the aerodynamic forces acting on groups of two and three circular cylinders when subject to a cross-flow. The study was conducted for a variety of geometrical patterns. In general it was found that the effect of cylinder displacement on the fluid forces for one cylinder in a group of three is very similar to that obtained with one cylinder in a group of two. Ng and Ko (1995) carried out numerical simulation of the incompressible flow past two circular cylinders placed side by side in a uniform stream. Depending on the transverse distances various modes of vortex shedding were identified. Mizushima and Takemoto (1996) performed flow visualization of the pattern downstream of a row of square bars. It was reported that for a

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specific Reynolds number and S/d combination, both flopping and bi-stable flip-flop behavior can exist downstream of the cylinders. Kolar et al. (1997) performed measurements on a pair of square cylinders using laser Doppler velocimetry at $Re=23{,}100$ and $S/d=2.0$. They examined the strengths of the vortices both near the gap and in the outer shear layers. Their results confirmed the dominant existence of antiphase synchronized pattern in the flow. Gu and Sun (1999) reported the results of a wind-tunnel investigation on the interference between two identical parallel circular cylinders arranged in staggered configurations at high subcritical Reynolds number. Valencia and Cid (2002) numerically investigated the unsteady turbulent flow and heat transfer in a channel with streamwise periodically mounted square bars arranged side-by-side to the approaching flow for a Reynolds number of 2×10^4. Balachandar and Parker (2002) addressed Hopf bifurcation and the associated Karman vortex shedding phenomena for a periodic array of rectangular cylinders in both inline and staggered arrangements. Mizushima and Akinaga (2003) investigated experimentally and also numerically the interactions of wakes for the flow past a row of square and circular bars. Their results showed that at $S/d=1.0$, in-phase vortex shedding occurs between cylinders whereas at $S/d=3.0$, anti-phase shedding was observed. Agrawal et al. (2006) performed numerical study of flow around a pair of square cylinders and showed the presence of synchronized and chaotic regimes with square cylinders at $Re=73$, in agreement with the well known results for circular cylinders. Inoue et al. (2006, 2007), in two consecutive articles, analyzed flow past two and three square cylinders placed in side-by-side arrangement in a uniform flow. They also

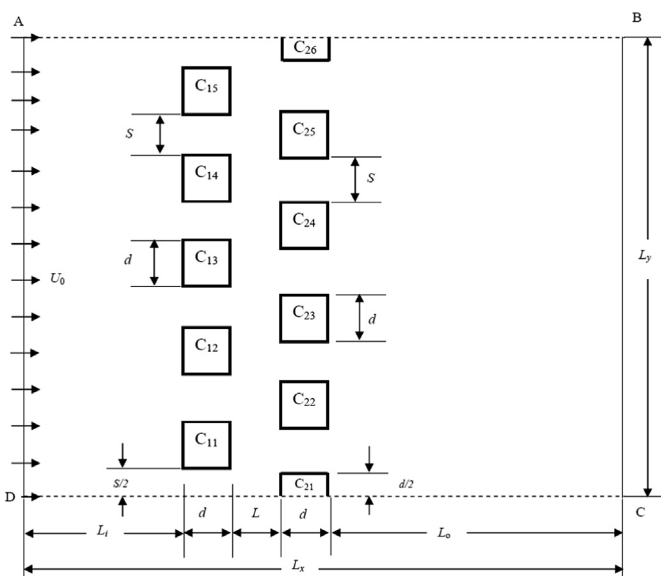

Fig. 1. Schematic of the computational domain.

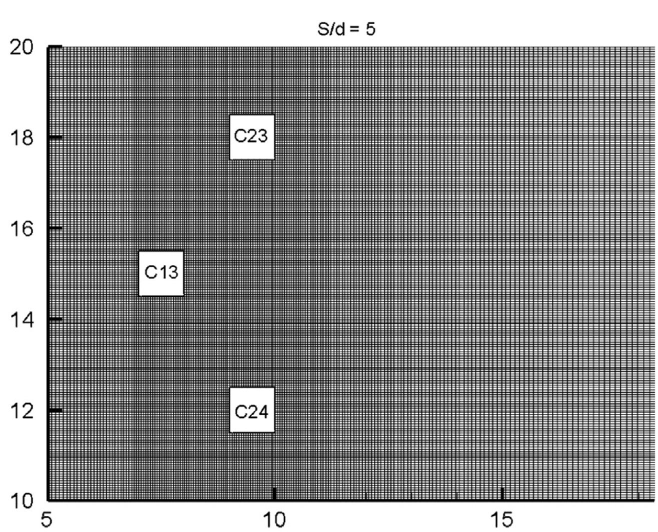

Fig. 2. Grid distribution, a closer view for S/d=5.

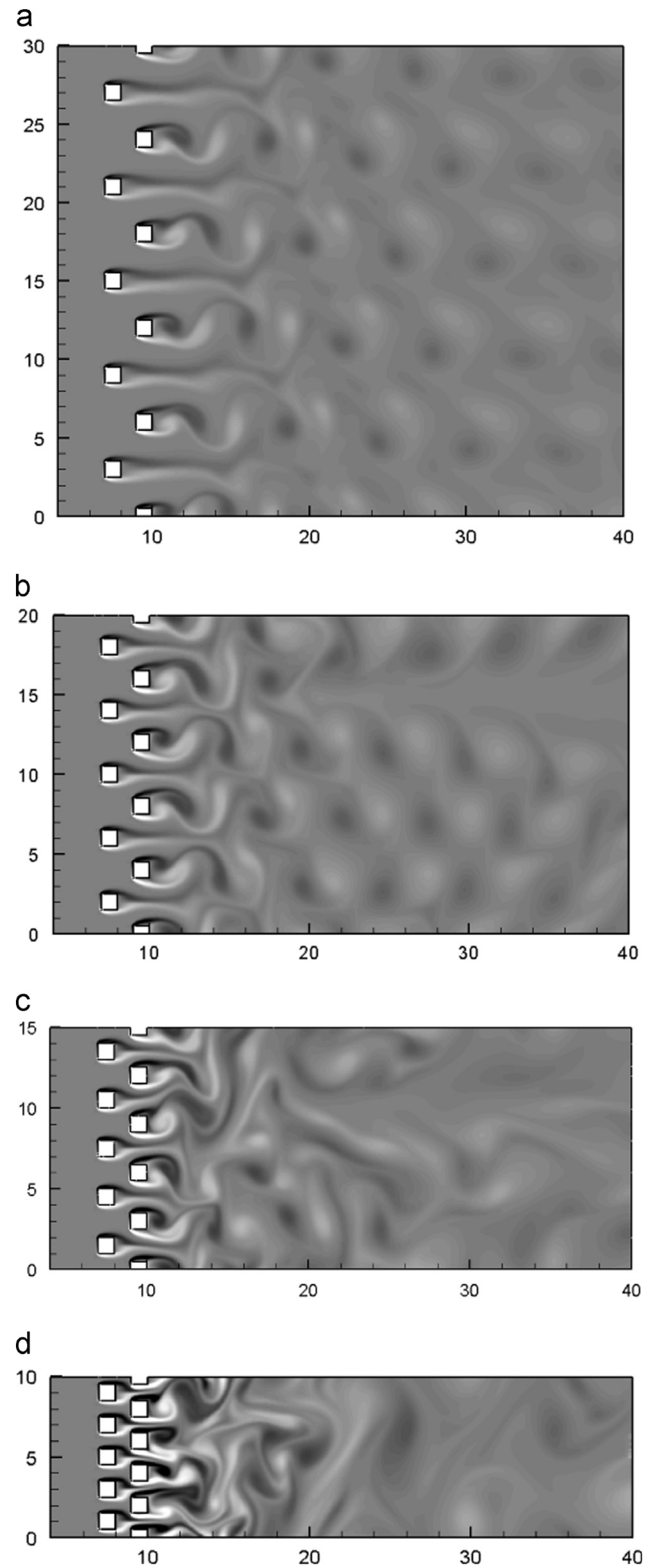

Fig. 3. Vorticity contour plots for (a) $S/d=5$, (b) $S/d=3$, (c) $S/d=2$ and (d) $S/d=1$ at $t=400$.