Investigation of Flow Interference Between Two Inline Square Cylinders With Different Spacing Ratios in Subcritical Reynolds Number Regime

Bhupendra Singh More, Manish Kumar Chauhan, Sushanta Dutta and Bhupendra Kumar Gandhi

Abstract When two cylinders are in proximity with each other the vortex shedding of one cylinder are influenced by the other. The flow field becomes even more complex when one cylinder subjected to an oscillation. In present study flow around two inline square cylinders of aspect ratio 50 at different spacing ratio is investigated experimentally. Experiments are performed for two identical square cylinders of 6 mm diameter at Reynolds number 500 in a low speed wind tunnel using Particle image velocimetry (PIV) and hotwire anemometer (HWA). The upstream cylinder is given predetermined oscillation and the gap between the two cylinders varied over wide range. Present study focused on effect of forcing frequency and spacing between centers of two cylinders (s/D = 1.5–5.0). The upstream cylinder is oscillated in transverse direction at $f/f_0 = 0$ to 2 and the effect of this oscillation is observed behind the downstream stationary cylinder at different spacing of the cylinders by hotwire.

Keywords PIV · HWA · Inline cylinder · Vortex shedding · Square cylinder

1 Introduction

A group of multiple bluff bodies depends on shape, orientation with respect to flow direction and spacing between the bodies. The numerous applications of group of multiple bluff bodies such as in high rise buildings, trailer trucks, bridge piers, flow around closely spaced electrical power poles, turning vanes in duct elbows, overhanging cables and heat exchangers. When square cylinders are grouped in tandem arrangement the flow field and aerodynamics forces are different from single cylinder. The presence of other bodies in the flow is called flow interference. We focused on flow interference in this paper, when the downstream cylinder in the

B.S. More · M.K. Chauhan · Sushanta Dutta (✉) · B.K. Gandhi
Mechanical and Industrial Engineering Department, Indian Institute of Technology, Roorkee 247667, Uttarakhand, India
e-mail: duttafme.iitr@gmail.com

A.K. Saha et al. (eds.), *Fluid Mechanics and Fluid Power – Contemporary Research*, Lecture Notes in Mechanical Engineering,
DOI 10.1007/978-81-322-2743-4_123

wake of another bluff body. Observed the combined drag force exerted on cylinders subjected to flow interference. The interference depends on the configuration of the two cylinders and their orientation to the free stream velocity. In the past many researchers have studied, two tandem circular cylinders, one of the earliest experimental studies on two cylinders in different configuration by Biermann and Herrnstein [1] then Zdravkovich [2] provides an excellent review work in this area, who classified the fluid behavior into three basic types of interference, based on the spacing between the cylinders. These three types of interference, and the conditions under which they occur, are (i) proximity interference, depends the spacing between two cylinders, in side by side and staggered arrangement (ii) wake interference, depends upon spacing in staggered and tandem arrangements, when one of the cylinders is partially or completely submerged in the wake of the other, and (iii) no interference. Gu and Sun [3] also classified the flow between the two circular cylinders, and divided the flow field into three different interference. (i) Wake interference when downstream cylinder is completely or partially submerged in the wake of upstream cylinder, (ii) shear layer interference when shear layer from upstream cylinder is reattached to the downstream cylinder and again separated and (iii) neighborhood interference, when synchronized vortex shedding from both the cylinders. Recent review on two circular cylinders by Sumner [4] identified nine flow patterns.

From the literature review it is seen that most of the work were carried out for circular geometry in the past, little considerable attention on square and rectangular geometries in recent years. For over a stationary cylinder and tandem arrangement the non—dimensional governing parameters are Reynolds number (Re), s/D ratio but for an oscillating cylinder the governing parameters are Re, s/D, amplitude ratio (A/D) (where A is peak to peak amplitude) and frequency ratio f/f_0.

The flow field of present study involves intricate interactions between the shear layers, wakes and Karman Vortex Street and these complexness increases further if upstream cylinder is oscillate in transverse direction at fixed amplitude ratio, (A = 0.1D) where the lock—in is observed in single cylinder case [5]. In the present case we study the effect of oscillation of the upstream cylinder on the flow structure and lock-in phenomena at different forcing frequency with fixed amplitude of oscillation. The results for the isolated square cylinder are first obtained. Then, the study two tandem cylinders are performed in stationary case and after that the oscillation of upstream cylinder is performed. The study has been carried out at a reduced velocity of 11.7 which is in the range of $7.3 \leq U/fD \leq 14.0$ [6].

2 Experimental Procedure

All experiments are conducted in a horizontal open ended sub sonic wind tunnel. A pair of identical square cylinders in cross-flow, the upstream is (mounted on electromagnetic actuator) subjected to force harmonic oscillation in the transverse direction and the downstream cylinder is mounted on side walls of test section. The

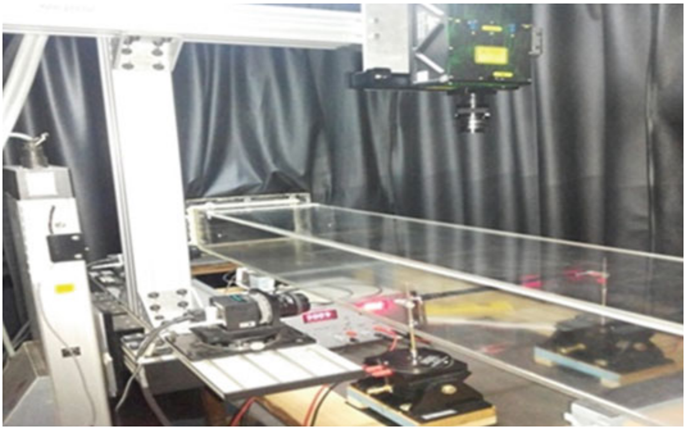

Fig. 1 Experimental setup with PIV and HWA

streamwise distance between cylinder centers are vary from (s/D) 1.5 to 5. The test-section 1800 mm long and 300 × 200 mm in cross-section as shown in Fig. 1. High quality flow in the test-section prevails with turbulence intensity of less than 0.08 %. The velocity profile of uniformity is measure at a distance 650 mm from inlet of test section and observed uniformity better than 95 % measured by micro-manometer, hotwire anemometer and PIV. The digital micro-manometer (Furness Controls, 19.99 mm H2O) is used to measure the free stream velocity (U).

The two cylinders are placed horizontally in the test-section for performing the experiments. The downstream square cylinder is fixed and changes its position to vary s/D ratios. Upstream one is mounted on an electromagnetic actuator, enabling forced transverse oscillations to the cylinder. The cylinder motions essentially a pure sine wave over wide range of frequencies (1–1000 Hz) in transverse direction provided by power oscillator which is calibrated by Laser Vibro-meter. The amplitude of oscillation is fixed for two cylinder arrangement is A = 0.1D. Both cylinders are constructed from aluminum of 6 mm square cross section and aspect ratio of 50. The blockage ratio for tandem arrangement was 3 %. The effect of end plates is checked and no end plates were used in present study.

PIV system is used to measure the velocity field over selected planes. A double-pulsed Nd:YAG laser (Ever Green Laser of wavelength 532 nm and 200 mJ/pulse) is used in PIV system. The images are recorded by CCD camera, a frame grabber, a synchronizer and a dual processor PC with Insight 3G software. The CCD is an array of 2048 × 2048 pixels. A Nikon 50 mm lens is connected to the CCD camera for capturing the selected planes which is illuminated by laser. The field of view for PIV measurements is 90 mm × 90 mm. From an initial size of interrogation size 64 × 64 pixels to final interrogation size of 32 × 32 pixels have been arrived at by an adaptive cross-correlation method. A total of 127 × 127 velocity vectors are obtained. The variation of time-averaged and rms velocity fields are checked by varying the number of images and we obtained a good agreement of 200 images for analysis the flow field. A TSI 6 jet atomizer is used to produce seeding particles from olive oil. Hotwire anemometer (DANTEC) is used to measure local time-averaged velocity and velocity fluctuations. Oscillation amplitude is estimated by calibration of electromagnetic actuators with laser Vibro-meter. The actuator frequency and amplitude are adjustable through a power oscillator. The upstream cylinder is oscillated in transverse direction at different harmonics of the vortex shedding frequency. The amplitude of oscillation (fixed A = 0.1D) is set by a voltage input to the electromagnetic actuator.

3 Results

The wake structure for multiple cylinder arrangement is completely different from a single cylinder. The flow interference of two square inline cylinders are carried out for two situations. In one case the upstream cylinder is given transverse oscillation with different frequency and fixed amplitude. In another case the gap between two cylinders varied over a wide range. The effect of frequency (f/f_0) and gap (s/D) are studied independently and near wake flow structure are mapped.

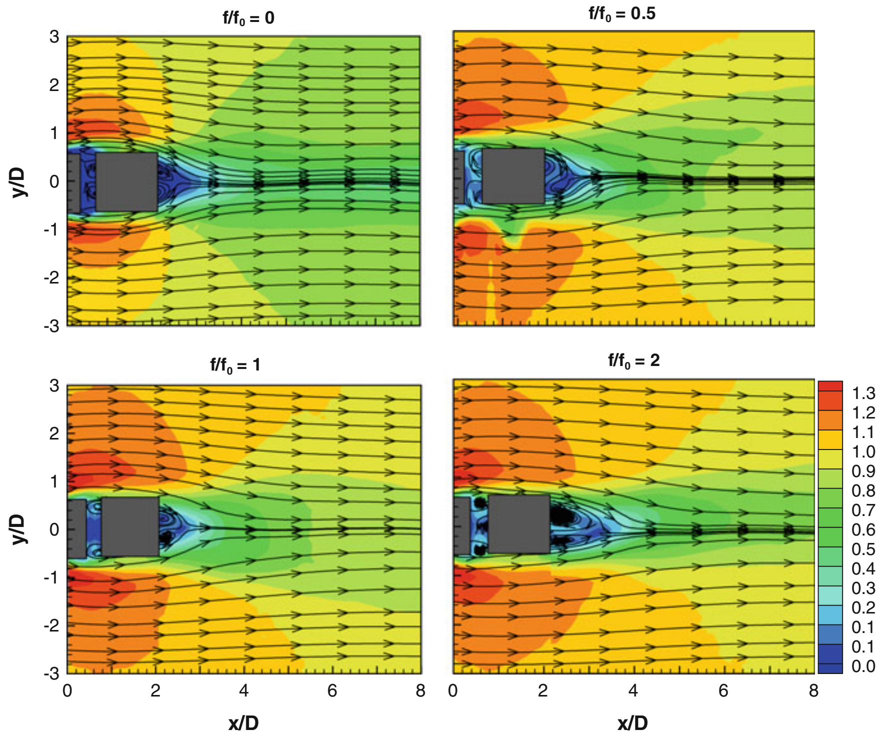

Fig. 2 Time-averaged velocity contours and stream line patterns for s/D = 1.5

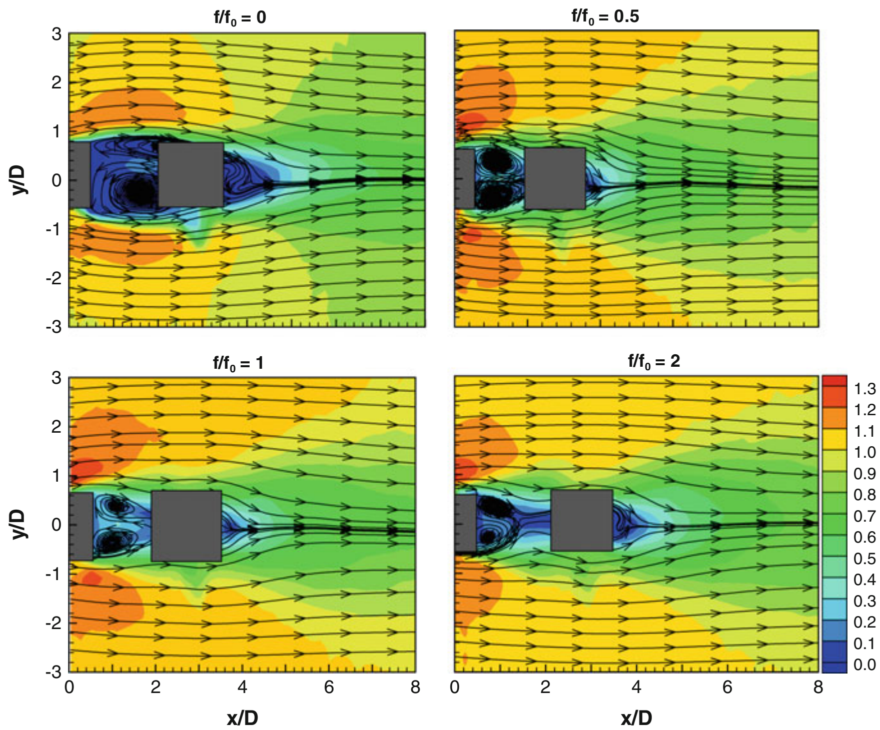

Fig. 3 Time-average velocity contours and stream line patterns for s/D = 3

3.1 Velocity Magnitude and Streamline Patterns

One of the cylinders (upstream) is mounted on electromagnetic actuator and the effect of its oscillation is observed behind the downstream cylinder. The time average velocity contours and streamline are measured by PIV. The normalized time average velocity contours and stream line patterns for the varying in center to center pitch ratio (s/D) from 1.5 to 5 and $f/f_0 = 0$ to 2 at Re = 500 are shown in Figs. 2, 3 and 4. The Reynolds number (Re) is defined as Re = ρUD/μ, where ρ is air density, U is free stream velocity, μ is the dynamic viscosity of air and D is the width of the square cylinder. The streamline patterns obtained for stationary cylinder in our experiments are well matches with the experimental works of S.C. Yen et al. [7]. For s/D = 1.5 the two bluff body act as a single extended body. Wake structure mainly depends upon the forcing frequency. At s/D = 3, the shear layers separated from the front corners of upstream cylinder are reattached to the downstream cylinder. The shear layer convection in streamwise direction slows down. The shear layers slowly glide over the downstream cylinder and delayed the vortex shedding mechanism. During the process, the shear layer gets sufficient time to adjust itself and small recirculation region formed behind the cylinder. With further

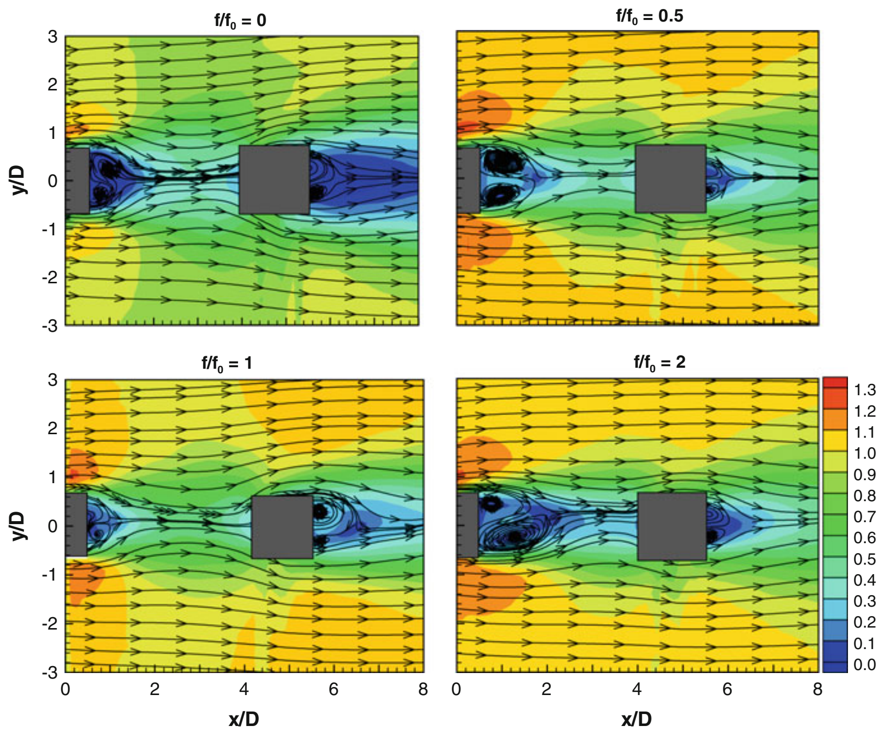

Fig. 4 Time-averaged velocity contours and stream line patterns for s/D = 5

increase in s/D ratio (s/D = 5), the vortex formation region of downstream cylinder do not get disturb by the presence of cylinder ahead of it. The Karman vortex shedding process of both the cylinders is independent. The upstream cylinder shedding process triggers the shedding of the downstream cylinder.

3.2 Flow Visualization, Instantaneous Vorticity Contours and Total Turbulence Intensity

Figure 5 shows the snapshot flow visualization images and instantaneous vorticity contours at s/D = 1.5 at same instant. The oscillation frequency of the upstream cylinder varied ($f/f_0 = 0{-}2$) with same amplitude ratio. Periodic shedding pattern get disturbed due to the transverse oscillation. For all the cases the shedding process starts very close to the cylinder as compare to single cylinder. The periodic shedding pattern completely suppressed at $f/f_0 = 0.5$. The wake structure become quite complex due to complex interaction of shear layer and three dimensionality starts appearing in the flow field. Figure 6 shows the comparison of total turbulence

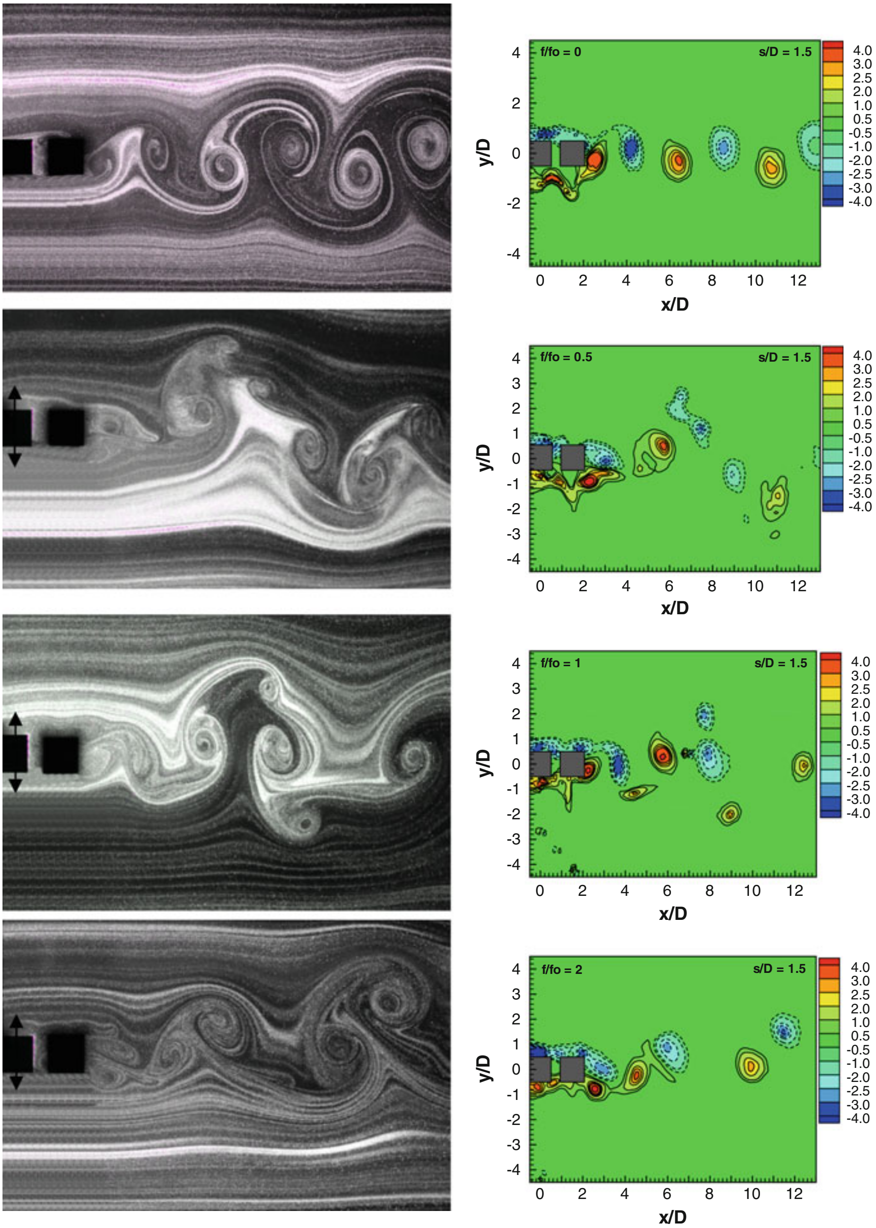

Fig. 5 Flow visualization images and instantaneous vorticity contours at s/D = 1.5 and $f/f_0 = 0{-}2$

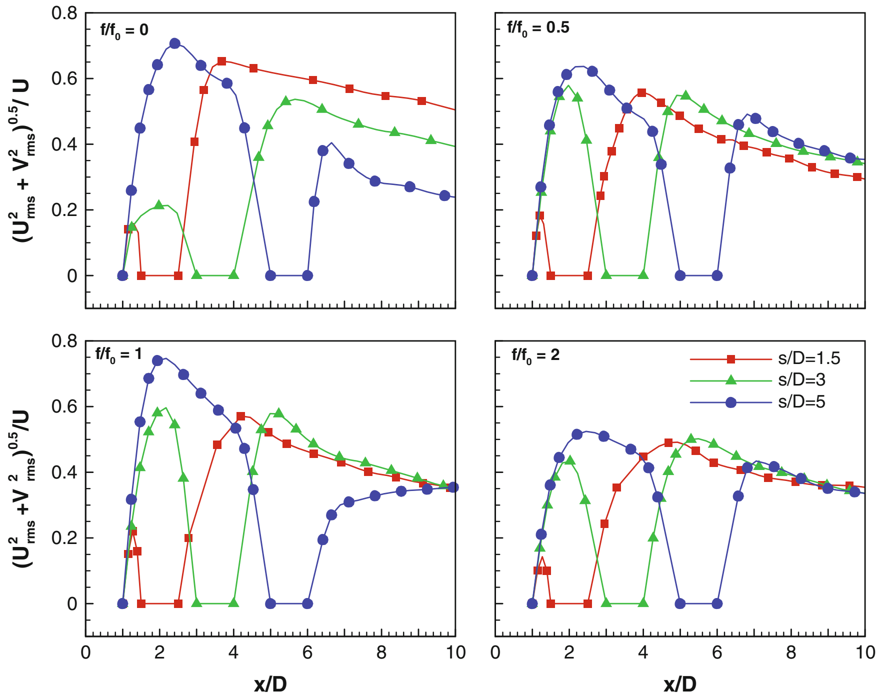

Fig. 6 Total turbulence intensity along centerline for different s/D ratios

intensity along the centerline for different s/D ratios at Re = 500. The total turbulence in downstream direction for stationary case is high at s/D = 1.5 compared with other spacing ratios. At these case two cylinders arrangement acts as a single extended body. When upstream cylinder oscillated in transverse direction the total turbulence in downstream direction is almost constant after 9D at harmonic and super harmonic case.

4 Conclusion

Flow field investigations of two inline square cylinders at stationary arrangement and at oscillating upstream cylinder arrangement have been studied experimentally by using PIV and Hotwire anemometer. The gap between the two cylinder varied over a wide range (s/D = 1.5−5). The upstream cylinder is given an oscillation in harmonics of vortex shedding frequency of stationary cylinder at constant amplitude. Three different flow regimes observed. At s/D = 1.5, the second cylinder acts as an extended body and periodic shedding have been observed. At s/D = 3, the separated shear layer from upstream cylinder reattached on the rear of downstream cylinder. Shear layer glided slowly over the cylinder and small recirculation zone formed. With further increase in gap ratio (s/D = 5), independent vortex shedding from both the cylinders. The Vortex shedding behind the fixed downstream cylinder is triggered by the oscillated upstream cylinder. Transverse oscillation of upstream cylinder change the flow structure is clearly observed in the wake structure.

References

1. Biermann, D., Herrnstein, W.H.: The interference between struts in various combinations. NACA Report No. 468 (1934)
2. Zdravkovich, M.M.: The effects of interference between circular cylinders in cross flow. J. Fluids Struct. **1**, 239–261 (1987)
3. Gu, Z.F., Sun, T.F.: On interference between two circular cylinders in staggered arrangement at high subcritical Reynolds numbers. J. Wind Eng. Ind. Aerodyn. **80**, 287–309 (1999)
4. Sumner, D.: Two circular cylinders in cross-flow: a review. J. Fluids Struct. **26**, 849–899 (2010)
5. Griffin, O.M., Ramberg, S.E.: The vortex street wakes of vibrating cylinders. J. Fluid Mech. **66**, 553–576 (1974)
6. Kumar, R.A., Gowda, B.H.L.: Flow-induced vibration of a square cylinder without and with interference. J. Fluids Struct. **22**, 345–369 (2006)
7. Yen, S.C., San, K.C., Chuang, T.H.: Interactions of tandem square cylinders at low Reynolds numbers. Exp. Thermal Fluid Sci. **32**(2008), 927–938 (2008)