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Phase Averaged Velocity Field in the Near Wake of a Square Cylinder Obtained by a PIV Method

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***Abstract*:** Phase averaged velocity fields in the near wake region behind a square cylinder have been successfully obtained using randomly sampled PIV data sets. The Reynolds number based on the flow velocity and the model height was 3,900. To identify the phase information, we examined the magnitude of circulation and the center of peak vorticity. The center of vorticity was estimated from lowpass filtered vorticity contours adopting a sub-pixel searching algorithm. Due to the sinusoidal nature of circulation which is closely related to the instantaneous vorticity, the location of peak vorticity fits well with a sine curve of the circulation magnitude. Conditionally averaged velocity fields represent the Karman Vortex shedding phenomenon quite successfully within $\pm 5^{\circ}$ phase uncertainty. The oscillating nature of the separated shear layers and the separation bubble at the upper and lower surfaces are clearly observed. With the hot-wire measurement of Strouhal frequency, we found that the convection velocity changes its magnitude very rapidly from 25 to 75 percent of the free stream velocity along the streamwise direction when the flow passes the recirculation region.

***Keywords*:** square cylinder, PIV, phase averaged velocity field, vortex tracking method, circulation.

1. Introduction

The wake flow behind a bluff body placed in a uniform flow is encountered extensively in engineering. High-rise buildings, chimneys and passenger cars are typical examples. The wake of the bluff body predominantly determines the distribution of forces as well as flow-induced vibration. Especially, the periodic motions associated with the large scale coherent structures created in bluff body wakes play a key role in the unsteady momentum transfer, so that researches about those structures turn out to be the most important theme for both numerical and experimental studies (Perry and Watmuff, 1981). However, it is extremely difficult to obtain an accurate velocity measurement in the near wake region because of its complexity and unsteadiness.

Compared with the flow around a circular cylinder, the turbulent flow around a square cylinder has not received much attention. The topology of both flow fields is expected to be identical, but differences in length and velocity scales are clearly apparent. In addition, the wake flow closer to the cylinder, within the first four diameters, has been less studied. This region exhibits high levels of mixing and the turbulent vortex street is fully developed. Because of the large-scale organized motion in the flow field around a bluff body, the time-varying component in the wake of a bluff-body flow includes a periodic component that may be distinguished from a residual 'random' component. The velocity signal is appropriately analyzed in terms of the triple decomposition of Reynolds and Hussain (1972).

Several techniques have been used in near-wake studies: flying-hot-wire anemometry (FHWA) (Perry and Steiner, 1987), Laser-Doppler velocimetry (LDV) (Owen and Johnson, 1980; Lyn et al., 1995), and particle image velocimetry (PIV) (Kim et al., 2000). The FHWA study of Perry and Steiner (1987) has reported phase-averaged statistics over any extensive region of the near wake behind a normal plate. Phase-averaging was based on a reference signal, either a pressure or a velocity signal, at a single point. Such a reference phase becomes less relevant at distances far from the location of the reference signal, leading to contamination of the phase-averaged statistics by phase jitter. Lyn et al. (1995) performed an LDV study of ensemble-averaged statistics at constant phase of the turbulent near-wake flow around a square cylinder at a Reynolds number of 21,400. Phase was defined with reference to a signal taken from a pressure sensor located at the midpoint of a cylinder wall.

As the PIV technique is introduced, it can be possible to acquire instantaneous velocity field. With ensemble average of the instantaneous realizations, we can measure highly accurate mean velocity field including a reverse flow region. However, it is not easy to have time dependent velocity field since the sampling frequency to obtain one instantaneous velocity field seems quite slow compared with the sampling time itself (Lourenco et al., 1997). In this study, we applied a new approach developed by Kim et al. (2000) to acquire the phase averaged velocity fields in the near wake of a square cylinder using PIV method. The center of vortex and the magnitude of circulation were chosen as the dependent variables on phase. The main purpose of this study is obtaining accurate phase averaged velocity fields to provide a bench mark data set for high Reynolds number wake flow behind a square cylinder.

2. Experimental Condition and Technique

2.1 Experimental Condition

Figure 1 represents the schematic of experimental setup and the coordinate system. Measurements were made in a small open circuit wind tunnel having a test section of 80 cm width, 30 cm height and 2 m length. Test section walls are made of plexiglass and glass plates. The air driven by a 3 hp variable speed centrifugal fan is supplied to the test section after passing a 2.67:1 two-dimensional contraction. The free stream turbulence at the test section was about 1%. The height of square cylinder was 20 mm and placed in the test section at 30 cm downstream from the end of contraction nozzle. The free stream velocity U_∞ was fixed to be 3.03 m/s, so the Reynolds number based on the cylinder diameter is 3,900.

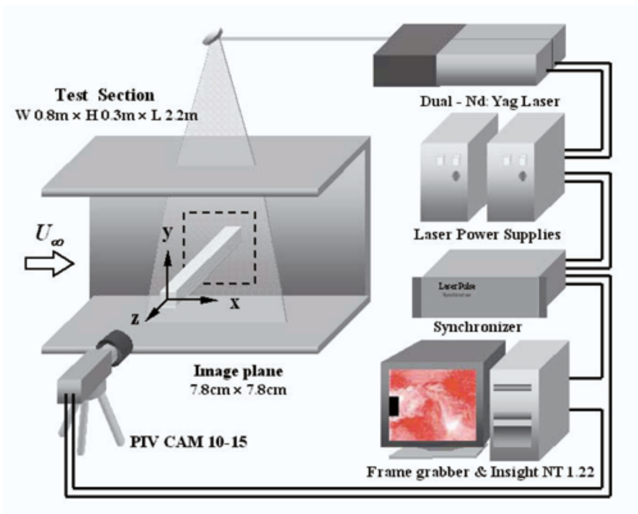

Fig. 1. Experimental setup and coordinate system.

The PIV system used in this study consists of a dual phase Nd:Yag laser, 1K by 1K high resolution CCD camera, a synchronizer (TSI 610032) and a Pentium computer which controls the PIV system. The seeding particle was olive oil aerosol having 2 ㎛ diameter generated by a Laskin nozzle made in our laboratory. The size of the field of view was selected as 78 mm × 78 mm and the velocity vector was obtained by the two frame cross correlation technique. The interrogation window was set to be 24 × 24 pixels and 50% overlap was permitted so that a total of 6,889 velocity vectors were obtained with a 0.93 mm spatial resolution. A post-processing software developed by Yoon (1999) was used to eliminate the spurious vectors, vortex center tracking, ensemble average, phase average and other statistical manipulations. In order to obtain the vortex shedding frequency, a hot-wire was placed in the cylinder shear layer at 1.5D downstream from the cylinder. This frequency was used to calculate the convection velocity and get the temporal information.

2.2 Phase Averaging Technique

Figure 2(a) depicts the ensemble averaged velocity field. A total of 2,030 instantaneous velocity fields are averaged. As shown in the figure, a perfect symmetric feature of velocity distribution is obtained with respect to the centerline. Although this nature never appears in the real circumstances, however it is useful to compare with any numerical simulation results. The size of the recirculation bubble is about 1.43D and the centers of the bubbles are found at x/D = 0.87 and y/D = ±0.39. The maximum reverse velocity is $-0.187U_\infty$ and appeared at x/D = 0.964 on the centerline.

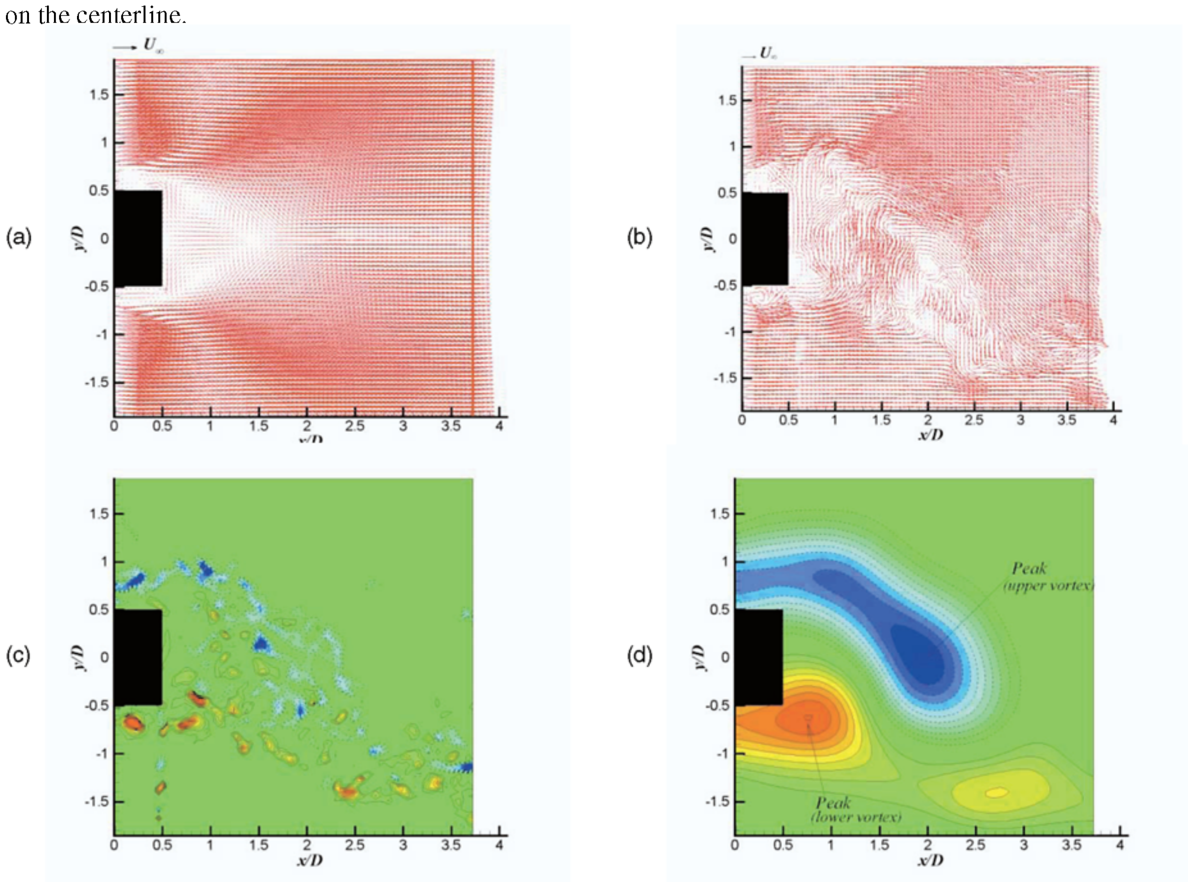

Fig. 2. (a) Ensemble averaged velocity field; (b) instantaneous velocity field; (c) instantaneous vorticity field; (d) lowpass filtered vorticity field.

Instantaneous velocity field and the corresponding vorticity field are shown in Fig. 2(b) and 2(c), respectively. The blue color denotes counter-clockwise rotation while red color means clockwise rotation of vortices. As can be seen in this figure, there finds hardly any centers of Karman vortices. Instead of the instantaneous vorticity field, the low pass filtered velocity field is used to detect the center of vortex motion as shown in Fig. 2(d). Many LES filters can be used to extract the large scale motion. In this study, we used a smoothing filter to the instantaneous velocity vector field for low pass filtering. The filtered vorticity field shows two distinct peaks of vortex motions which are denoted as "upper" and "lower" vortex center. Only maximum value of the vorticity was selected to determine the representative vortex center at a given instant.

Figure 3(a) demonstrates the locations of shedding vortices which are obtained from the low pass filtered vorticity fields from 2,030 instantaneous velocity realizations. Since the location of the peak vorticity has a spatial uncertainty with the grid size of the velocity vector, it is needed to search the peak vorticity up to the sub-grid scale. Knowing that the distribution of vorticity turns out to be a Gaussian distribution, the center points are identified in the sub-grid level using a Gaussian fitting function (Westerweel, 1993) .

Though there exists some scattering, the trajectory of the vortex centers cross together at y = 0, but not like a straight line. It is noted that the mean trajectory of shedding vortices merges together about x/D = 1.5 which is

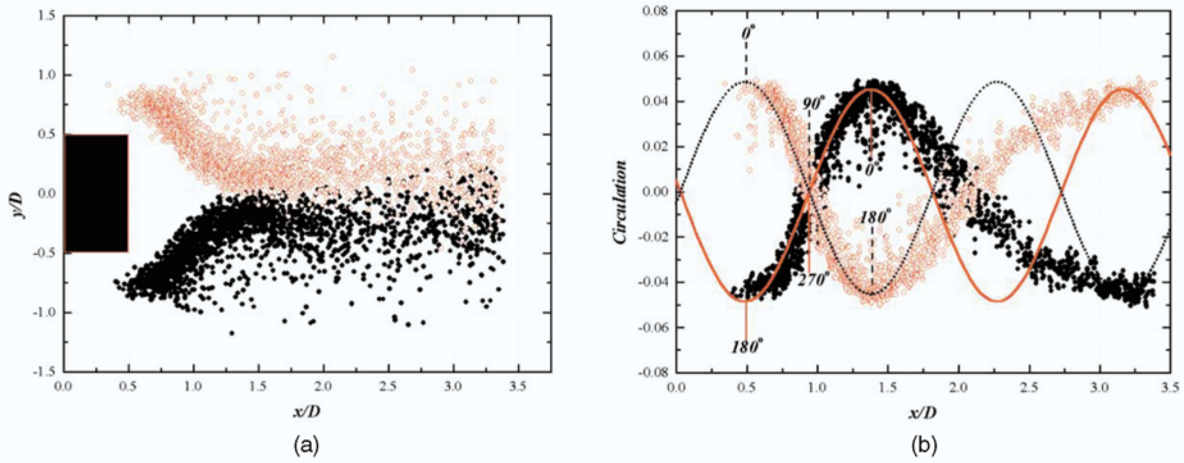

Fig. 3. (a) Vortex center trajectory (○: upper vortex, ●: lower vortex); (b) Variation of the circulation with the location of the vortex center. A sine wave is added to obtain the phase estimation.

coincidence with the end point of the recirculating flow region. The most striking feature is that the scattering of the vortex center seems quite severe after merging. From this result, one can imagine that the conventional method of conditional sampling using a reference probe may have a frequency jittering effect.

Kim et al. (2000) used circulation value obtained by instantaneous velocity field to get a relevant information of the phase of shedding vortices. They found that the location of vortex is highly depended on the phase of circulation of the shedding vortices for the case of circular cylinder wake. In this study, we calculated circulation value of the instantaneous velocity field along the rectangular path made by $1.1D \leq x \leq 1.745\ D$ and $-\ 0.34D \leq y \leq 0.305D$. The domain includes the cross position of the vortex center which is the end of recirculation region, so that it may represent the periodical nature quite strongly.

Figure 3(b) illustrates the position of the vortex center at the given magnitude of circulation. The value of circulation versus the location of the vortex center has been fitted by sine function curves as appeared in Fig. 3(b) as the solid and dotted lines. Up to x/D = 1.5, the circulation follows the sine wave quite well, therefore it is reasonable to accept that the value of circulation corresponds to the phase. We defined the phase 0° when the center of lower vortex locates at the end of recirculation region with a maximum value of circulation as shown in Fig. 3(b).

3. Results and Discussion

3.1 Turbulence Spectrum and Convection Velocity

Since hot-wire experiment reveals local pointwise information, it is usually cumbersome to map the flow field in all aspect. Instead, the power spectrum of fluctuating velocity component determined at selected location in the wake can shed light on the wake dynamics. Figure 4 shows velocity spectrum taken at x/D = 2.5, y/D = 2.0 in which Karman vortex edges are passing the probe. A dominant peak at the shedding frequency, f = 20.75 Hz, is clearly seen in Fig. 4 at a Reynolds number of 3,900.

The resulting Strouhal number, $St = f\ D/U_\infty = 0.136$ agrees well with the previous studies. Okajima (1982) reported that there exists a constant Strouhal number of 0.133 for a range of Reynolds number, $1{,}000 < Re_D < 20{,}000$ when a square cylinder is situated in a uniform flow with 0.5% of free stream turbulence. Lyn et al. (1995) measured the Strouhal number to be 0.132 ± 0.004 for a square cylinder wake at the Reynolds number, 21,400 by LDV.

The convection velocity of the vortex center can be estimated by mutiplying the vortex shedding frequency with the wave length of a sinusoidal function of circulation. The longer the wave length, the faster the convection velocity. From Fig. 3(b), the streamwise convection velocity varies from $0.245U_\infty$ at $x/D < 1.5$ to $0.75U_\infty$ at $x/D > 4$. Lyn et al. (1995) reported that the convection velocity of the vortex structure motion is $0.43U_\infty$ for $x/D < 3$ and $0.78U_\infty$ for $x/D > 4$. The two results yield a good agreement. The present result concludes that there exits an acceleration of the convection velocity in the near wake region, so a single choice of a reference frame velocity can be made only a single structure.

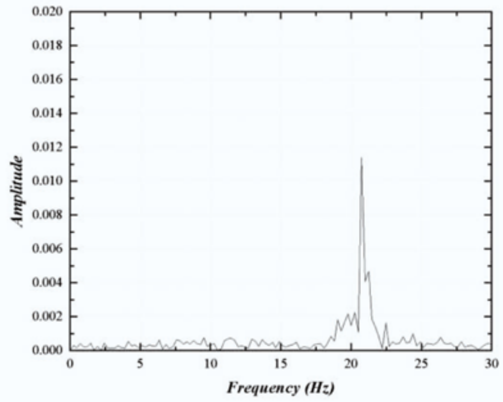

Fig. 4. Power spectrum of streamwise velocity fluctuation.

3.2 Phase Averaged Velocity and Vorticity Fields

All velocity fields occuring within the same phase bin with a ±5° interval constituted an ensemble at constant phase. The ±5° interval corresponds ±0.5 mm in spatial distance. The number of samples in a bin varied depending on measurement phase, about 60 – 70 samples even we have 2,030 instantaneous velocity fields. This number could be enough for ensemble averaged velocity field, however too small to estimate higher order statistics.

Figure 5 shows the estimated phase averaged velocity fields. We defined 0° of phase where the circulation value reaches its maximum. Physically, this condition reveals that a fully developed counter-clockwise vortex locates at the end of recirculation zone where the value of circulation is evaluated. Totally opposite manner could be seen in the velocity field at 180° of phase. A fully developed clockwise rotating vortex from the upper edge is depicted in this phase. From 45° of phase, one can see the starting vortex of clockwise rotation generated from the upper edge. At 90° of phase, the clockwise vortex becomes bigger, while the counter-clockwise vortex seems to disappear. It should be pointed out that the disappeared counter-clockwise vortex can be seen if the reference frame is moving with the vortex convection velocity. Further growth of clockwise vortex can be seen at 135° of phase. It is interesting to note that the center of vortex follows the dividing streamline of the ensemble averaged velocity field. From 180° to 315° of phase, the evolution of counter-clockwise vortex from the lower edge is clearly seen and exactly opposite with those obtained from 0° to 135° of phase with respect to the centerline.

Figure 6 demonstrates the phase averaged vorticity fields. Alternate shedding of vortical structures is clearly seen in this figure. Highest values of vorticity occur at the shear layers on both upper and lower vertex of the square cylinder due to the steep gradient of velocity. Because of the separation bubble at upper and lower edges, opposite value of vorticity appears between the shear layer and the cylinder wall. Note that the separation bubble moves back and forth with respect to the phase.

4. Conclusion

Phase averaged velocity fields in the near wake region of a square cylinder at 3,900 Reynolds number have been successfully measured by the vortex tracking method with randomly acquired PIV data sets using a conditional statistics method. The location of vortex centers from upper and lower vortices is found from the low-pass filtered vorticity fields with a sub-pixel accuracy. It is verified that the value of circulation instead of temporal signal gives not only the phase information but also the dynamic characteristics of the vortex structure. The convection velocity is estimated from the wave-length of the circulation curve with the hot-wire measurement of vortex shedding frequency. It is found that the convection velocity changes its value considerably in the near wake region from 25% to 75% of the free stream velocity. The obtained phase averaged velocity and vorticity fields clearly show the periodic nature of the Karman vortex street. Both topology and velocity data associated with phase could be useful to verify numerical simulation results such as an LES method.

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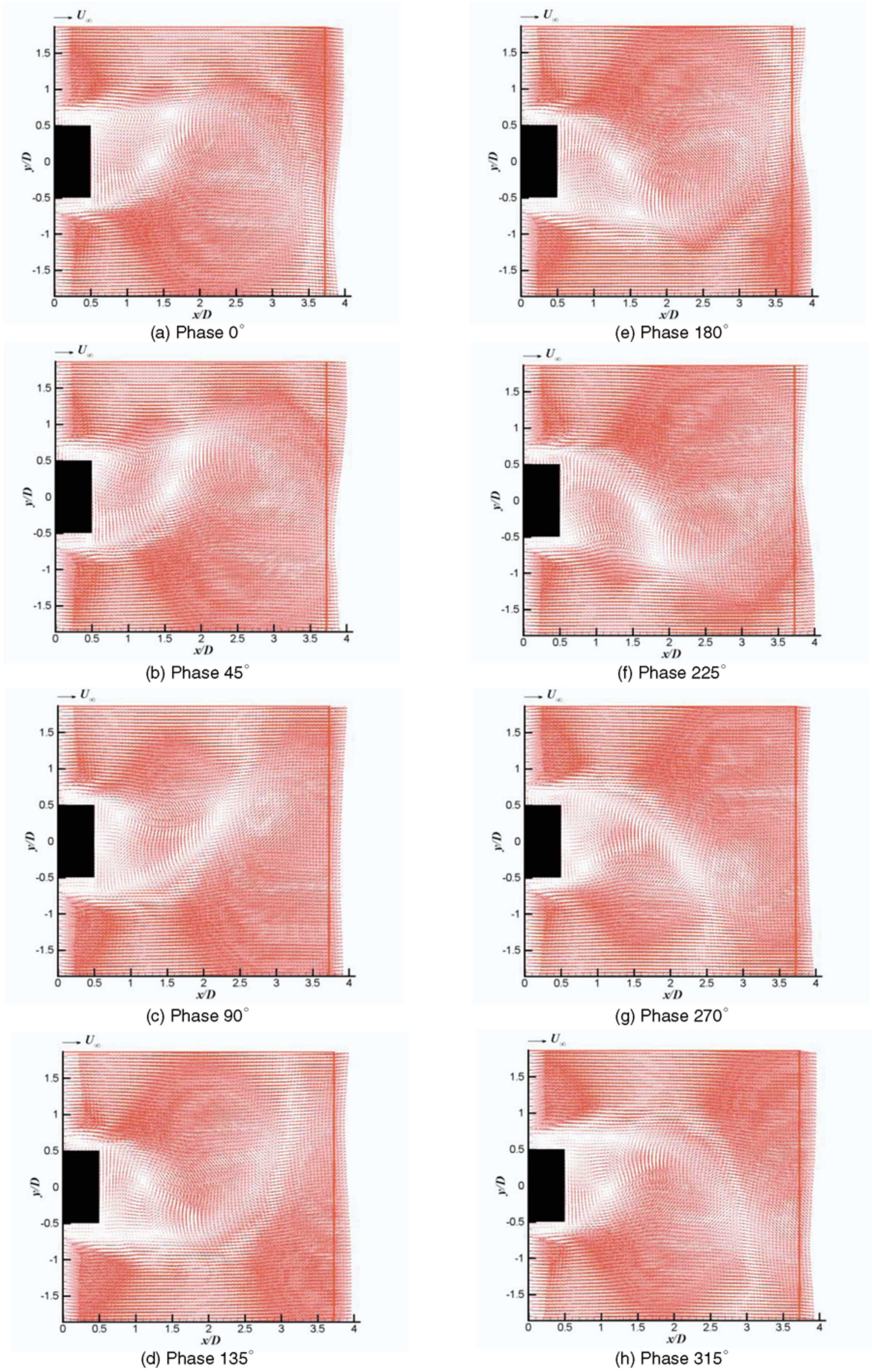

Fig. 5. Phase averaged velocity fields according to phases.

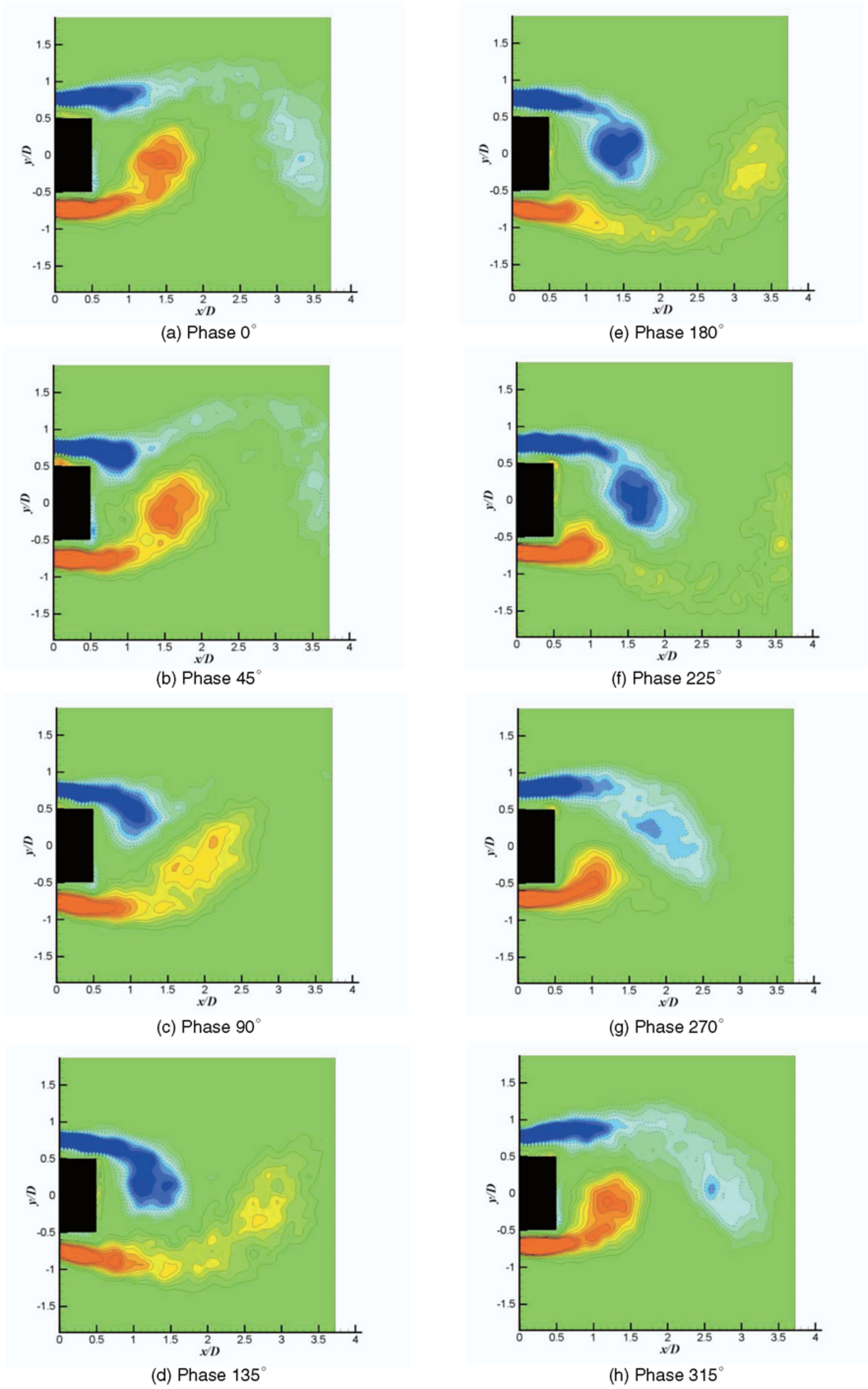

Fig. 6. Phase averaged vorticity fields according to phases.

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