Flow structure in the downstream of square and circular cylinders

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Abstract

In this experimental work, a technique of digital particle image velocimetry (DPIV) is employed to characterize instantaneous vorticity and time-averaged velocity, vorticity, root mean square (rms) velocities, Reynolds stress correlations and phase-averaged contours in the downstream of circular, sharp-edged square and 45° orientated square cylinders in a uniform flow. Strouhal numbers for $550 \leq Re \leq 3400$ are calculated from wake flow patterns. Shear layers surrounding the recirculation bubble region behind the cylinder are discussed in terms of flow physics and vortex formation lengths of large-scale Kármán vortices. Enhancement levels of Reynolds stress correlations associated with cross-stream velocity are clarified. Finally, flow structures depending on the cylinder geometry and Reynolds number are interpreted with quantitative representations.

Keywords: Square cylinder; Circular cylinder; DPIV; Vortex shedding; Wake region; Strouhal number

1. Introduction

The motion of fluid passing circular or square cross-section cylinders is encountered in numerous industrial applications, as well as offshore and environmental settings, including tall buildings and structures such as bridges, chimneys, trash racks, cooling towers, heat exchangers, etc. When fluid flows around any bluff body, the vortices are alternatively shed and a well-known Kármán vortex street is formed in the wake of the cylinder. The oscillating wake rolls up into two staggered rows of vortices with opposite senses of rotation. The frequency of vorticity pairs is a function of velocity, cylinder diameter and Reynolds number [1]. The vortex shedding frequency of the circular cylinder is normalized by Strouhal number, $St = f_s D/U_\infty$, where $f_s$ is the dominant vortex-shedding frequency, $D$ is the cylinder diameter and $U_\infty$ is the freestream flow velocity. The vortex shedding frequencies and flow configurations are major issues for the design of structures. The flow in the near-wake region behind the cylinder, incorporating the vortex formation region, plays an important role in determining the steady and unsteady forces acting on the body. Periodic vortex shedding patterns and fluctuating velocity fields

behind the bluff bodies can cause structural damage as a result of periodic surface loading, acoustic noise and drag forces [1,2]. Most work has been done on the flow passing a circular cylinder (CC) rather than a square cylinder (SC). Even though their near-wake flow structures are expected to be topologically similar to one another, the reasons for flow separation on the cylinder surfaces are totally different. That is, flow separation occurs due to an adverse pressure gradient in the downstream direction for the CC and the separation points on the CC surface move back and forth depending on the Reynolds number. However, the locations of the separation points are fixed at the upstream corners of the SC due to the abrupt geometrical changes.

Relevant investigations for the SC and the CC include those of Okajima [3], Obasaju [4], Durao et al. [5], Lyn et al. [6], Saha et al. [7], Dutta et al. [8], Chen et al. [9], Sarioğlu and Yavuz [10] and Roshko [11] using measurement techniques such as dye visualization, point-wise hot-wire/film and laser Doppler velocimetry (LDV) for various Reynolds numbers. Okajima [3] carried out an experimental study of flow past the SC as well as the rectangular cylinder for $70 \leq Re \leq 20,000$ to determine the vortex shedding frequencies. The results showed that there was an abrupt change in Strouhal number when the aspect ratio of the cylinder was reduced to the range 2–3. Strouhal numbers for the SC with an increasing angle of incidence from 0° to 45° were examined using a hot-wire probe in a closed circuit wind-tunnel for $Re = 10,000$ by Obasaju [4].
LDV measurements were conducted for flow past the SC in a water tunnel for $Re = 14,000$ and $Re = 21,400$ [5,6]. Durao et al. [5] separated the periodic and random components of velocity fluctuations around the SC. The experiment results of Lyn et al. [6] showed a relationship between the flow topology and turbulence distribution. They clearly distinguished vorticity saddles and streamline saddles. Measurements were reported of two components of velocity in the wake for Reynolds numbers of the SC such as 1340, 4990 and 9980 for various inclinations such as $0^\circ$, $22.5^\circ$, $30^\circ$, $45^\circ$, and $60^\circ$ by using smoke visualization and a hot-wire anemometer [7,8]. Saha et al. [7] stated that, though the overall flow past the SC resembled that of the CC, there were major differences in terms of the separation mechanism and the related integral parameters such as Strouhal number, lift and drag coefficient. Vortex-shedding frequencies and surface pressures of the SC, CC and rectangular cylinders in a wind tunnel were investigated experimentally using hot-film measurement techniques [9,10]. They determined the dominant peak location of the vortex shedding frequency and obtained Strouhal numbers in the range of various Reynolds numbers for the CC, SC and oriented square cylinder (OSC). The various aspects of the quasi two-dimensional (2-D) and three-dimensional (3-D) structures of the shear layer vortices, as well as the correlation of their frequency with Reynolds number for the CC, were also given by Roshko [11].

In recent decades, flow structures around CC has been investigated quantitatively by Lin et al. [12]. They employed the film based particle image velocimetry technique at three values of $Re = 1000$, 5000 and 10,000 for the CC to obtain instantaneous flow patterns. They stated that representations of velocity, vorticity and streamlines showed a decrease in vortex formation length with increasing Reynolds number. Noca et al. [13] accomplished an investigation on the concept of vortex formation length in the wake of the CC by measuring the location of some easily identifiable flow features for $300 < Re < 4000$ and different aspect ratios. An alternative approach was to interpret the vortex formation length on the basis of a characteristic velocity fluctuation in the streamwise direction given first by Bloch and Gerrard [14] and Szepessy and Bearman [15]. The large variation in the formation length of Kármán vortices over the range of Reynolds numbers from 5000 to 40,000 was observed qualitatively by Schiller and Linke [16]. Balachandar et al. [17] applied direct numerical simulations at the lower $Re$ number and large-eddy simulation at the higher Reynolds number over several different 2-D bluff bodies for $250 \leq Re \leq 140,000$. They also performed experiments to support their numerical solutions. They investigated properties of the time- and phase-averaged mean wake recirculation region in the separated flows. They explained the distribution of Reynolds stress and pressure in relation to the mean wake recirculation region (wake bubble) and vortex formation length. The response of the SC that was free to rotate in a uniform flow was solved numerically using the 2-D incompressible time dependent Navier–Stokes equation, which was also examined experimentally on fixed and freely rotating cylinders for $1000 \leq Re \leq 10,000$ by Zaki et al. [18]. In order to obtain flow characteristics and develop reliable computational methods, numerical simulation studies of 2-D and 3-D unsteady flows around the SC have been addressed [19–24]. Reviews and assessments of concepts, numerical simulations, and experimental observations for bluff bodies are given by Williamson [1], Ahlborn et al. [25], Knisely [26] and King [27]. Although many of the above investigations are experimental and based on flow visualization and/or point-wise measurement techniques such as LDV or hot-wire anemometry to obtain instantaneous flow characteristics, a few issues have remained unresolved for this class of near-wake flows. Specifically, none of the foregoing investigations attempted to measure quantitatively the details of the separated shear layers and the overall properties of the flow in separated regions for the SC using DPIV.

The purpose of this study is to investigate the effects of the cross-section of the vertical cylinder perpendicular to the oncoming flow and the Reynolds number in terms of instantaneous and time-averaged velocity, vorticity, streamline topology, and Reynolds stress correlations along with root mean square (rms) velocity. First of all, Strouhal numbers are calculated for the sake of comparison. The physical origins of loading coefficients and flow-structure interactions have been interpreted. Phase-averaged vorticity and velocity patterns are examined. Moreover, the turbulence properties of the wake, most importantly the Reynolds stress correlations, have been addressed in relation to Reynolds numbers for the SC and CC. Finally, interpretation of the effect of the Reynolds number on the vortex formation length and width of the wake size has been determined quantitatively. Informative data for both numerical simulations and designers have been provided.

2. Experimental system and technique

The experiments were performed in a closed-loop free-surface water channel of width $W = 1000$ mm, length $8000$ mm and free-surface height $H = 750$ mm. The test section is preceded by a 2:1 contraction ratio and flow conditioning, which provided a free stream turbulence intensity of less than 0.2% in the range of Reynolds numbers from $Re = 550$ to $3400$, where $Re = (U_\infty D)/\nu$, based on the CC diameter and width of the SC. Here, $\nu$ is the kinematic viscosity. An overview of the experimental system for the SC case is shown in Fig. 1. Aspect ratios were 30 and 50 with respect to the submerged section and the whole length of the cylinder, respectively. A sharp-edged end plate of 800 mm $\times$ 800 mm $\times$ 13 mm was located on the bottom surface of the water channel as shown in Fig. 1. The purpose of using the end plate was to reduce the three-dimensional flow and deflection effects. The SC, of 20 mm $\times$ 20 mm with sharp-edged cross-section, was made of plexiglass. On the other hand, a circular plexiglass cylinder of 20 mm diameter had a hollow cross-section.

An Nd:Yag laser was used to generate a laser sheet perpendicular to the axis of the cylinder, and a CCD camera with a resolution of $1024 \times 1024$ pixels was used to record the images (see Fig. 1). The thickness of the laser sheet was around 1.5 mm. The laser sheet was located horizontally at a height of $h_L = 330$ mm above the channel’s bottom surface,
while the water height was $h_W = 600$ mm in all cases. The seeding particles in the flow were silver-coated hollow glass spheres with a diameter of 15 $\mu$m. The specific gravity of the seeding particles, provided by Potters Industries Inc., was 1.10. The densities of the particles and water were close enough so that the distribution of particles in suspension remained uniform for several hours. A Dantec DPIV system was used to measure velocity vectors. In image processing, a spot size of $32 \times 32$ pixels was used to allow effective interrogation. During the interrogation process, an overlap of 50% was employed in order to satisfy the Nyquist criterion. Furthermore, to satisfy the high-image-density criterion, the interrogation window typically contained 20–30 particles per image. Finally, 200 instantaneous velocity vector fields were collected at the rate of 15 Hz for each Reynolds number. The time delay between pulses ranged from 1 ms to 12 ms. In-house software was used to evaluate and remove inappropriate displacement vectors (less than 1%), caused by shadows, reflections, or laser sheet distortions in the flow field and replaced by using bilinear interpolation between surrounding vectors in the post-processing step. The field was then smoothed by a Gaussian weighted averaging technique. To minimize distortion of the velocity field, a smoothing parameter of $\sigma = 1.3$ was chosen. After producing the vector field, the vorticity patterns of the wake flow were determined by using a finite difference scheme. For all the experiments, image magnification was 1:5.91, which yielded an effective grid size of $2.75 \text{ mm} \times 2.75 \text{ mm}$ in the physical plane of the laser sheet, corresponding to 3844 velocity vectors. The overall field of view was $171 \text{ mm} \times 171 \text{ mm}$ ($8.5D \times 8.5D$) in all cylinders.

Adrian [28] and Westerweel [29] provided very detailed information about particle image velocimetry. The uncertainty factors for velocity measurement and vorticity calculation in the DPIV method mainly comprised of the seeding particle size, non-uniform particle distribution, particle overlap, unmatched particle correlations, out of laser plane motion (bias and random errors), interrogation window size, and electronic and optical imaging noise. The details of the effects of these factors can be found in the studies of Adrian [28], Westerweel [29], Keane and Adrian [30], Fournas and Soria [31], and Hart [32]. Factors contributing to uncertainty in the velocity measurement using the DPIV technique were critically assessed, Westerweel [29] concluding that uncertainty estimation in the velocity measurement was less than 2%.

3. Results and discussion

3.1. Spectral analysis and calculation of vortex shedding frequency

The dominant vortex shedding frequency $f_s$ is determined from power spectra of recorded DPIV data in the near-wake region of the cylinders, particularly inside the free shear layer region, at the various selected points. Statistical characteristics of the instantaneous streamwise velocities in time series are determined in order to get information in the frequency domain by using spectral analysis, i.e. Fast Fourier Transformation (FFT). FFT analysis in the wake of the body reveals significant quasi-periodic flow oscillations. As is known, the most powerful spectral peak reflects the vortex shedding frequency in the spectra. Input data number for frequency spectra should be power of 2. It was obtained from padding time-averaged value of 200 DPIV instantaneous velocities at the end of time history of the velocity in order to extend input data number to the value of 4096 samples, for each spectrum analysis in Fig. 2. Depending on the locations where the spectral measurements are calculated, the magnitudes of the spectral peaks varied with the Reynolds number and bluff body shape. Spectral peaks do have different dominant frequencies and magnitudes due to the different shape and the separation points, as displayed in Fig. 2, even though the cylinders have the same nominal diameter and symmetrical configuration to the oncoming flow. The results of the FFT calculation point out that dominant frequencies at the selected points are approximately equal in the $x$ and $y$ directions, i.e. cross-stream and streamwise velocity components. Here, only the streamwise velocity component result is presented, but Strouhal numbers in various positions of the wake region are calculated and given as mean values in Table 1 for $550 \leq Re \leq 3400$. All Strouhal numbers presented for the 45° OSC were based on the projected cross-section of the cylinder. In Fig. 2, Strouhal numbers at $Re = 3400$ are obtained as 0.21, 0.13 and 0.165 for the CC, SC and OSC, respectively. The peak values of the vortex shedding frequencies at the upper and lower wake region of the cylinder are the same, which are 1.75, 1.12 and 1.05 Hz for the CC, SC and OSC, respectively. The spectrum magnitude of the peak frequency for the SC is larger than that of the CC due to the higher rate fluctuations.
Fig. 2. Time history of instantaneous streamwise velocity component \( u \) (mm/s) against time \( t \) (s) and spectrum analysis \( S_u \) at denoted point with black donut on the small image at \( Re = 3400 \) for CC (top), SC (middle) and OSC (bottom).

3.2. Instantaneous and time-averaged flow patterns

Representative instantaneous vorticity contours of the wake structure for the CC, SC and OSC geometries at \( Re = 550 \) and \( Re = 3400 \) are illustrated in Fig. 3 for Case A and Case B. The instantaneous vorticity \( \omega \) is normalized as \( \omega^* = \omega/(U_\infty/D) \). The results of many qualitative and quantitative investigations explain the well-known Kármán vortex shedding. In Case A, there is a large-scale Kármán vortex in the upper side of the cylinder, whereas for Case B the same flow behaviors occur from the alternate direction, i.e. the lower side of the cylinder in Fig. 3. Viewing the vortex street in the cross-sectional plane gives the appearance of the upper row of negative vortices (dashed lines) and the lower row of positive vortices (solid lines). Flow entrainment to the rear of the cylinder coming from the upper side of the cylinder reverses the clockwise direction, whereas that from the lower side of the cylinder rotates in the anticlockwise direction. These are known shear layers, and alternatively rolls up to form the vortices in the wake as follows. One of these shear layers coming from the opposite side of the cylinder entrains into the growing shear layer of the other side of the cylinder in the wake region. This induces the detachment of the longer shear layer vortex from the cylinder. Shorter vortex shedding located near the cylinder has a rotating reverse flow towards the cylinder, which detaches the vortex from the cylinder surface and initiates production of the next vortex. On the one hand, the flow separation points in the middle column images of Fig. 3 occur at the left-side corners of the SC. On the other hand, the separation points are delayed up to the cylinder corners in the downstream side for the OSC, as seen in the right-hand column of Fig. 3.

Instantaneous vorticity patterns in Fig. 3 clearly present the interaction between the shear layers formed on both sides of the cylinder. It is demonstrated that the SC has a wider wake region than that of the CC for all flow patterns. This effect contrasts with the increase in the transverse direction, which blocked the flow and thus causes an increase in drag force. Dutta et al. [8] recorded similar observation through the smoke visualization of flow around the SC. The Reynolds number plays an important role in flow structure even if the bodies have sharp edges, as seen in Fig. 3. Instantaneous vorticity patterns quantitatively indicate the remarkable decrease in the formation length of the large-scale Kármán vortex with

originating from sharp-edged corners, as displayed in Fig. 2. The difference between the \( St \) values for the CC, SC and the OSC might be explained by the different nature of their flows. For the SC at an angle of incidence (0° and 45°) to the flow and for the CC, the Strouhal numbers given in Table 1 were measured by a number of authors. Table 1 clearly indicates that the present results are in close agreement with most of the previous experimental and numerical results for all cylinders. The results of the present work for the SC agree well with the results of [3,9,22]. King [27] reported that the non-dimensional wake Strouhal number for the CC was \( St \approx 0.21 \) over a wide range of Reynolds numbers, for example \( 10^2 < Re < 10^5 \). In the present study, Strouhal numbers obtained for the CC almost matched the value of 0.21 generally found in the literature. The Strouhal number at \( Re = 3400 \) for the CC is around 38% and 19% higher than the SC and OSC, respectively. It is worth nothing that there are some discrepancies between the obtained results and some of the previous studies, as seen in Table 1. Possible sources of these discrepancies could be the difference in Reynolds number among the various results, a different blockage ratio, the aspect ratios of the model, the experimental setup, surface roughness, wind tunnel or water channel, the turbulence intensity of the free-stream flow, end conditions, and tiny nonparallel effects [3,11,22,33,23,34]. Strouhal numbers given in Fig. 2 and Table 1 for the present investigation are based on evaluations of a spectral frequency interval, of about 0.004 Hz, corresponding to a resolution of about 3% in terms of the dominant vortex shedding.
Table 1
Comparison of Strouhal numbers

<table>
<thead>
<tr>
<th>Authors</th>
<th>Re</th>
<th>SC</th>
<th>OSC</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>550 to 3400</td>
<td>0.120 to 0.134</td>
<td>0.165 to 0.174</td>
<td>0.204 to 0.212</td>
</tr>
<tr>
<td>Okajima [3]</td>
<td>500 to 3400</td>
<td>0.121 to 0.128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saha et al. [7]</td>
<td>500</td>
<td>0.135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dutta et al. [8]</td>
<td>1340</td>
<td>0.142</td>
<td></td>
<td>0.191</td>
</tr>
<tr>
<td>Chen and Liu [9]</td>
<td>2000 to 3400</td>
<td>0.125</td>
<td>0.172</td>
<td></td>
</tr>
<tr>
<td>Zaki et al. [18]</td>
<td>1790 and 2450</td>
<td>0.120 and 0.122</td>
<td>0.156 and 0.161</td>
<td></td>
</tr>
<tr>
<td>Saha et al. [19]</td>
<td>500</td>
<td>0.120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sohankar et al. [21]</td>
<td>500</td>
<td>0.122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hwang and Sue [22]</td>
<td>500 and 1000</td>
<td>0.125 and 0.137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Davis et al. [23]</td>
<td>500 and 1000</td>
<td>0.140 and 0.150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim et al. [24]</td>
<td>500 and 3000</td>
<td>0.120 and 0.125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knisely [26]</td>
<td>2200</td>
<td>0.125</td>
<td>0.160</td>
<td>0.21</td>
</tr>
<tr>
<td>Norberg [35]</td>
<td>550 to 3400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nakagawa et al. [36]</td>
<td>3000</td>
<td>0.130</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of patterns of dimensionless instantaneous vorticity \( \omega^* \) for \( Re = 550 \) (top two rows) and \( Re = 3400 \) (bottom two rows) is presented. Both minimum and incremental contour levels of positive (solid line) and negative (dashed line) dimensionless instantaneous vortices in all images are 0.5.

increasing Reynolds number. The vortices produced at the corners of the SC have a tendency to displace in the inward direction because of lower pressures prevailing within the wake. This is counter-balanced by the growing wake size, which shifted the vortex centerline outwards. It is evident that the flow characteristics in the downstream of the SC and OSC are more complicated than the CC. In fact, at \( Re = 3400 \) for the OSC, the large-scale clusters of vortices induce negative vorticity layers that are immediately adjacent to the base of the cylinder as seen in the right-hand column of Figs. 3 and 5, as displayed for Case A and time-averaged vorticity \( \langle \omega^* \rangle \). Regarding the onset and development of small-scale vortical structures in the separating shear layer, regions of low-level vorticity concentration are discernible in the pattern of instantaneous vorticity for \( Re = 550 \) and \( Re = 3400 \) in Fig. 3. Large-scale Kármán vortices for the SC and OSC form in the near-wake region due to the abrupt coalescence of small-scale shear-layer vortices in the separating shear layers that are similar to the CC work of Lin et al. [12]. Instantaneous vorticity patterns showed the irregular vorticity shapes, and the shear layers tend to break up easily into
small concentrations of vorticity related to Kelvin–Helmholtz instabilities. They seem to combine into larger vortices during the process of formation and shedding, as shown in Fig. 3. For \( Re = 3400 \), these concentrations become more pronounced, and small-scale structures are clearly evident inside as well as at the periphery of the large-scale vortex. Concentrations of small-scale vortices for the OSC are the greatest.

Comparison of patterns of normalized time-averaged vorticity \( \langle \omega^* \rangle = \langle \omega \rangle / (U_\infty / D) \), streamline topology \( \langle \psi \rangle \), streamwise velocity \( \langle u^* \rangle = \langle u \rangle / U_\infty \), cross-stream velocity \( \langle v^* \rangle = \langle v \rangle / U_\infty \), rms contours of the streamwise velocity \( \langle u'_{\text{rms}} \rangle = \langle u_{\text{rms}} \rangle / U_\infty \) and cross-stream velocity \( \langle v'_{\text{rms}} \rangle = \langle v_{\text{rms}} \rangle / U_\infty \) and Reynolds stress correlations \( \langle u'v' / U_\infty^2 \rangle \) for the CC, SC and OSC are presented for \( Re = 550 \) and \( Re = 3400 \) in Figs. 4 and 5, respectively. Time-averaged vorticity patterns \( \langle \omega^* \rangle \) clearly reflect the changes in the formation length of the large-scale vortices in the first rows of Figs. 4 and 5. It is observed that the streamwise location at which the minimum positive and negative contour lines approach each other near the symmetry plane of the wake is an indicator of the time-averaged vortex formation length. It is evident that the vorticity contours for all cylinder cases are deflected inwards at a location immediately downstream from the base of the cylinder at \( Re = 3400 \). This type of inward deflection
occurs at a distance significantly further downstream from the base of the cylinder at $Re = 550$. For low $Re$ number, a large-scale vortex appears within the flow field further downstream. However, at successively higher Reynolds number, such as $Re = 3400$, it moves further upstream and is closer to the base of the cylinder. In the first row of Figs. 4 and 5, the time-averaged vorticity images reveal that the detailed instantaneous structure of the small-scale vortices and the far downstream part of the Kármán vorticity street are lost due to the unsteady flow structure and alternating direction of the vortex shedding from both sides of the cylinders. In the base region, two separated shear layers with oppositely signed vortices interact more directly and vigorously, resulting in substantial cancellation of the averaged vorticity, as seen in Figs. 4 and 5. The streamwise separation length of successive vorticity peaks in the near-wake region for the OSC is larger and longer than that of the CC and SC. This is more apparent in the first row of Fig. 3. The shape of vortex contours in the near-wake is similar for both geometries of the CC and SC. Comparison of the time-averaged vorticity patterns $\langle \omega^* \rangle$ and streamline topology $\langle \psi \rangle$ with each other and itself shows that flow structures of the wake are almost equally symmetrical with respect to the centerline of the CC, SC and OSC for $Re = 3400$. Patterns of time-averaged streamline topology
identify the major changes of the near-wake behind the cylinders. They exhibit well-defined critical points, e.g. foci (centers of vortices) designated as F₁ and F₂ and saddle points (apparent intersections of streamlines) denoted as S, as shown in the second row of Fig. 4 for the OSC, and symmetrical flow structures for the CC, SC and OSC in the second row of Fig. 5. From the averaged streamline patterns in Fig. 4, the streamline shapes extending upstream to the near-base region of the CC and SC are elliptical and have a limited spiral cycle focused very close to the upper side of the downstream boundary of the SC and the lower side boundary of the CC due to insufficient capture time and data numbers. It is worth emphasizing that computer controlled data acquisition systems could not allow capturing and processing DPIV data numbering more than 200. Specifically for Re = 3400, whole-field representations of streamline patterns, along with the identification of the locations of these types of critical points, could provide an insight into the effective formation length of large-scale vortices and the degree of symmetry of either side of the near-wake. Streamline saddles in the near-wake similarly correspond to the time-averaged zero vorticity contour. The non-dimensional wake lengths (L/D) measured from the center point of the cylinder to the saddle point in the averaged streamline topology (ψ) for Re = 3400 in Fig. 5 are approximately 1.65, 1.23 and 2.20 for the CC, SC and OSC, respectively. These values become around 2.75, 1.92 and 4.0 for the CC, SC and OSC, respectively, for Re = 550, as seen in the second row of Fig. 4.

Representations of the streamwise velocity component (u*) over the entire field of view are also given in the third row of Figs. 4 and 5. Substantial regions of negative (reverse) flow are evident at Re = 550 and Re = 3400 for minimum and incremental contour levels. From these images, it is also possible to define the location of a stagnation point around the wake symmetry plane, which is designated by a black dot. The distances from the center point of the cylinders to the stagnation point at Re = 550 in Fig. 4 are approximately 2.4D, 1.9D and 4.3D for the CC, SC and OSC, respectively. The locations of the stagnation points at Re = 3400, which become around 1.7D, 1.2D and 2.2D for the CC, SC and OSC, respectively, move upstream, as seen in the third row of Fig. 5. Viewing the patterns of Figs. 4 and 5 as a whole, the effect of orientation of the OSC substantially increases the streamwise length of the separated vorticity layers relative to the case for the CC and the SC. Then, the growth of the separated shear layers from the cylinder shoulders is associated with an increase in the wake size for the OSC. Another important parameter of the wake is the non-dimensional width (W/D) of the wake can be defined as the cross-stream distance between extrema of the time-averaged vorticity layers on opposite sides of the wake. For example, quantitative interpretations of the wake width from the time-averaged vorticity, corresponding to lateral distances passing through maximum and minimum contour values in the top row of Fig. 5, are respectively 0.95D, 1.48D and 1.76D for the CC, SC and OSC at Re = 3400. On the other hand, these values for Re = 550 are 1.21D, 1.54D and 2.17D for the CC, SC and OSC, respectively. At these locations, as well as at locations downstream, local bulges of the cross-sectional patterns of the wake are evident; they are consistent with regions of abrupt wake widening observed in the sectional patterns of the flow structure for the SC and OSC, as seen in Figs. 3–5.

Patterns of time-averaged cross-stream velocity ⟨u*⟩ are given in the fourth row of Figs. 4 and 5. The patterns of cross-stream velocity are detectable near the interface between the separating shear layers. Moreover, it is accompanied by a decrease in the streamwise extent of the separation bubble at Re = 3400 relative to the bubble length at Re = 550. The contours of constant cross-stream velocity ⟨u*⟩ close to the base of the cylinder have relatively larger values for Re = 3400. A large amplitude of cross-stream velocity ⟨u*⟩ at Re = 3400 might indicate that the developing shear layers which originally separate from the CC, SC and OSC entrained a significant mass flow in the base region through both sides of the cylinder. A possible explanation for this phenomenon is an increase in the level of Reynolds stress in the separating shear layer, as seen in the bottom rows of Figs. 4 and 5. It might be concluded from pattern concentrations that Reynolds stress correlations have considerably enhanced values at Re = 3400 with regard to Re = 550.

The time-averaged contours of the Reynolds stress correlation ⟨u’v’/U* DM⟩ associated with rms streamwise velocity ⟨u* rms⟩ and the cross-stream velocity component ⟨v* rms⟩ are shown in the bottom three rows of Figs. 4 and 5. The rms flow patterns display similar behaviors, not only for different Reynolds numbers but also for the CC, SC and OSC, whereas they have discrepancies from the points of the flow pattern concentrations and vortex formation lengths. At Re = 3400, the fluctuations and irregularities are greater for the SC and OSC than the CC in the separating shear layer. The rms streamwise velocity patterns ⟨u* rms⟩ have easily detectable double peaks at almost equal locations in the upper and lower sides of the cylinder centerline for all cylinders presented in Fig. 5, which are placed around 1.6D, 1.5D and 1.8D for Re = 3400 for the CC, SC, and OSC, respectively. The maximum contour values of ⟨u* rms⟩ for Re = 550 in the centerline of the wake occur at nearly 3.1D, 2.5D and 4.3D, whereas these distances for Re = 3400 decrease to approximately 2.5D, 2.2D and 4.1D for the CC, SC and OSC, respectively. Cross comparison of the results reveals double peaks for ⟨u* rms⟩, while a single peak is observed in ⟨v* rms⟩ with a maximum occurring along the centerline axis of the vortex near to a location coincident with the stagnation point in the downstream of the cylinders.

Reynolds stress correlations ⟨u’v’/U* DM⟩ depict a set of extrema on either side of the wake centerline for the CC, SC and OSC in the bottom rows of Figs. 4 and 5, which provide a direct comparison of patterns for two Reynolds numbers from the point of momentum transfer. The patterns in the Reynolds stress correlations consist of both small-scale clusters located in the vicinity of the base of the cylinder and large-scale clusters located just downstream from the small-scale clusters. The well-defined Reynolds stress patterns due to the fluctuations in the shear layers produce a weaker Reynolds stress region very close to the base of the cylinder which occurs as a result of the flow entrainment into the wake region. The basic forms
of these patterns persist for $Re = 550$ and $Re = 3400$. The extrema of the large-scale contours for $Re = 3400$ are displaced downstream by distances of nearly $2.1D$, $1.8D$ and $2.4D$ with regard to the center of the CC, SC and OSC, respectively. However, these distances have larger values at $Re = 550$ and reach $2.8D$, $2.3D$ and $4.1D$ for the CC, SC and OSC, respectively. The upstream extension of each large-scale cluster of $(u'v'/U_{\infty}^2)$ migrates further upstream and the tip of the large-scale clusters is located closer to the base of the cylinders for $Re = 3400$ in Fig. 5. As clearly displayed in the bottom row of Figs. 4 and 5, this large-scale cluster migration is the greatest for the OSC. This trend is in accord with the earlier appearance of the confined small-scale concentrations of vorticity in the shear layer, as indicated in the corresponding instantaneous images in Fig. 3. Same-signed Reynolds stress correlation patterns $(u'v'/U_{\infty}^2)$ and cross-stream velocity components $u^{*}$ extend one side of the centerline to the other for all cylinders. The patterns of Reynolds stress correlations occur over a larger extent across the wake for the OSC. Peak values of Reynolds stress correlations increase in the base region and then decay sharply in the wake region, as seen from the concentrations of the flow structure. Reynolds stress correlation $(u'v'/U_{\infty}^2)$ is zero around the cylinder axis as a result of symmetrical flow structure for $Re = 3400$ and attains its greatest magnitude in the upper and lower regions of the centerline, although peak values of $(u'^{*2}_{rms})$ occurred at the axis itself. Thus, velocity fluctuations penetrate deeper into the outer flow and finally cause an increase in the drag coefficient as a result of increased wake size. The Reynolds stress correlations in and around the mean wake recirculation region are primarily due to the time-dependent nature of the vortex shedding. In this limit, it is observed that the Reynolds stress correlation is relatively small in the outermost region of the flow patterns, as displayed in the bottom images of Figs. 4 and 5. Despite the significant differences in the geometry of the bluff body, the distributions of Reynolds stress patterns around the wake bubble for the SC and OSC are quantitatively similar to the CC in the range $550 \leq Re \leq 3400$. However, the measured values of the peak Reynolds stresses are somewhat higher for the SC and OSC than those of the CC. Furthermore, the peak values of normalized Reynolds stresses $(u'v'/U_{\infty}^2)$ for the CC, SC and OSC are 0.08, 0.12 and 0.14 for $Re = 3400$, respectively.

3.3. Comparison of phase-averaged and instantaneous images

In addition to time-averaging, phase-averaging images have been pursued. In cases where a periodic signal is recorded along with the DPIV images, it is possible to employ this signal as a phase-reference, provided that the timing of DPIV images is known. Patterns of normalized phase-averaged vorticity $(\omega^*)_{p} = (\omega)/U_{\infty}/(D)$, streamwise velocity $(u^*)_{p} = \langle u \rangle / U_{\infty}$ and cross-stream velocity $(v^*)_{p} = \langle v \rangle / U_{\infty}$ for the CC, SC and OSC at $Re = 3400$, corresponding to representative instantaneous patterns of vorticity $\omega^*$, are given in Fig. 6.

Calculations of phase-averaged flow patterns have been accomplished as follows. First of all, a movie of instantaneous vorticity patterns is created by using cinema in a sequence of 200 instantaneous vortices. As seen from the time history of the streamwise velocity component $u$ at any point in the field of view shown in Fig. 2, there are around 14 and 25 vortex-shedding cycles (periods) of the SC and CC cases, respectively. Each period includes approximately 7 and 15 instantaneous images in sequence for the CC, SC and OSC, respectively. Second, according to the instantaneous streamwise velocity component $u$, any point in the wake region of 7 or 15 images captured during the vortex shedding period is chosen for the CC, SC and the OSC as a reference frame. Third, this velocity component is compared with the instantaneous streamwise velocity component $u$ of other periods of images in a sequence at the same location. Fourth, when they are close to each other within the accepted experimental accuracy, the vorticity patterns of these two instantaneous images are compared with each other by superposition. Finally, the most similar 11 images of each respective phase of the vortex shedding cycle are chosen to obtain phase-averaged flow patterns for the SC, OSC and CC, separately. Average relative errors of the phase-averaging method between instantaneous velocity component $u^*$ and phase-averaged velocity component $(u^*)_p$, which are obtained from point to point in the field of interest shown in Fig. 6, are less than 4%, 8% and 9% for the CC, SC and OSC, respectively. These phase-averaged images, which emphasize the large-scale repetitive vortical structures, are intended to serve as a guide for the interpretation of instantaneous vorticity patterns $\omega^*$. Formation of the large-scale vorticity clusters of vortices and from Kármán-like vorticity is barely discernible in the patterns of instantaneous vortices $\omega^*$ for all cylinders in Fig. 6. Furthermore, large-scale concentrations of vorticity are clearly evident in both the upper and lower side layers of the cylinder for phase-averaged vorticity, as well as the further wake region. The upper layer is deflected substantially downwards from its shedding location, while the lower layer acts in the reverse direction. Viewing the patterns of phase-referenced $(\omega^*)_p$ and instantaneous vorticity $\omega^*$ as a whole, similar vorticity layers are obviously obtained from phase-averaged patterns for all cylinders. For the cases of the CC, SC and OSC, it is evident that small-scale vorticity concentrations occur in the separated shear layer for all cases, as is clearly seen from the instantaneous vorticity patterns shown in Figs. 3 and 6. These small-scale concentrations in vorticity probably come from the 3-D nature of the separated flow. However, phase-averaging cancels out these vorticity layers, while preserving the identity of large-scale Kármán vortices. In the third row of Fig. 6 for all cylinders, phase-averaged streamwise velocity $(u^*)_p$ shows that rolled up flow originally starting from the upstream side of the SC, OSC and CC is conveyed downstream together with the corresponding Kármán vortex; they form a counter-rotating flow pair. Hence, the cylinder wake greatly enhances the mixing process of the flow. The wake region of the OSC for phase-averaged streamwise velocity $(u^*)_p$ is the widest. The wavelengths from one pocket center to other, placed around the same lateral location for phase-averaged streamwise velocity $(u^*)_p$, are approximately 3.8D, 3.2D and 2.6D for the CC, SC and OSC, respectively. In viewing all images in Fig. 6, phase-averaged flow patterns reveal the alternate staggered nature.
Fig. 6. Comparison of dimensionless instantaneous vorticity and phase-averaged flow patterns at \( Re = 3400 \) for the CC, SC and OSC.

of the vortex street, thus signifying a dominant periodicity in the flow, as seen in Fig. 2. In these so-called staggered patterns, both positive and negative concentrations of phase-averaged cross-stream velocity \( \langle v^* \rangle_p \) exist at a given spanwise location. However, the wavelengths of phase-averaged cross-stream velocity \( \langle v^* \rangle_p \) have two values for negative and positive clusters for all cylinders. The wavelengths between the positive centers of \( \langle v^* \rangle_p \) are around 3.8\( D \), 5.7\( D \) and 5.1\( D \), which are closer to the cylinder base region, shorter than that of negative one, and have values of nearly 3.0\( D \), 4.4\( D \) and 3.9\( D \) for the CC, SC and OSC, respectively. The reasons for the differences in the wavelengths might be the higher convective speed of the vortices and the absence of the strong interaction between the oppositely signed vortices in the far-wake of the cylinder.

4. Conclusions

This investigation focused on the generation of vortical structures of the near-wake region arising from flow passing the CC, SC and OSC for 550 \( \leq Re \leq 3400 \) in order to explain the physical mechanisms of the flow structure. The present paper has supported the previous works by providing detailed quantitative experimental information with DPIV in the near-wake region of the CC and SC. It is found that the values of Strouhal number, as well as the wake patterns, are functions of the cross-section of the cylinders and Reynolds numbers. Strouhal numbers for the CC, SC and OSC are found around 0.21, 0.13, and 0.17, respectively.

Quantitative comparison of the CC and SC show that length scales are larger for the SC, not only in the cross-stream direction but also in the stream-wise direction. Owing to the fixed separation points of the SC, the flow separation and the recirculation regions have an increasing effect in the wake region. On the other hand, the size of the wake region and the distance between oppositely signed vortices increase due to the 45° orientation effect of the SC. The flow patterns have considerable symmetry about the centerline of the cylinders of the flow patterns, as shown in all time-averaged images for \( Re = 3400 \). However, unsymmetrical flow structures are obtained for \( Re = 550 \) because of the insufficient data numbers. Contours of the time-averaged streamwise velocity demonstrate that the stagnation point around the symmetry plane moves further upstream for higher \( Re \). Time-averaged cross-stream velocity contours \( \langle v^* \rangle \) and Reynolds stress correlations, which are oriented in the direction of each respective shear layer separation from the cylinder, are important features of the near-wake structures from the point of momentum transfer, as \( Re \) becomes larger. In terms of the concentration values of the flow patterns for three different cases, the peak value of the OSC is slightly higher due to the stronger rotational fluid motion in the wake region than that of the CC and SC. The shear layer surrounding the recirculation bubble behind the cylinders
has a region of intense velocity fluctuation with high values of Reynolds stress correlation because of the vortex interactions. Patterns of \(u'v'_{\text{rms}}\) and \(u'U_{\infty}^2\) have indicated double peaks, whereas that of \(u'_{\text{rms}}\) shows only a single peak. The vortices shed from both sides of the cylinder are the source of these two minima in the flow contours. It is physically confirmed that the predominant features of the instantaneous and phase-averaged vortices are closely correlated, thereby reaffirming the use of instantaneous vorticity patterns as representations of the flow.

In general, vortex formation lengths decrease with increasing Reynolds number for all the patterns presented. Present results can provide sufficient information about the details of the foregoing flow features to develop a strategy for the validation of numerical models in the future.

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