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High-definition PIV Analysis on Vortex Shedding in the Cylinder Wake

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Abstract : A high-definition analysis based on flow topology is made on the vortex motions under natural and lock-on conditions in the near-wake region of a circular cylinder, where two-dimensional flow fields in the wake-transition regime are measured by a time-resolved PIV system. The Reynolds stress distributions are examined in view of the mean separation streamline and the trajectory of the vortex center. It is shown that, by the lock-on, the Reynolds stresses become stronger and their dispositions match well with the shortened wake bubble, indicating perfect synchronization of shedding to the oscillatory forcing flow in the near field, which causes increased lift and drag forces.

Keywords : Time-Resolved PIV, Trajectory of Vortex Center, Wake Bubble, Lock-on

1. Introduction

Vortex dynamics, which govern the evolution and interaction of coherent structures and coupling of coherent structures with background turbulence, is promising not only for understanding turbulence phenomena such as entrainment and mixing, heat and mass transfer, chemical reaction and combustion, drag, and aerodynamic noise generation, but also for viable modeling of turbulence (Hussain & Melander, 1991). We must identify dynamically significant, large-scale vortical regions in turbulent flows as a necessary first step, which in turn necessitates an objective definition of a vortex. Vortex definition has been a very important research topic until nowadays. Meanwhile, a considerable amount of work has been carried out on the coherent structures in the near wake of a circular cylinder for laminar, transitional and turbulent flows. They have been constantly of great research interest because even at low Reynolds numbers, of the order of a few hundred, the flow has three-dimensional structures. Until the shear layer vortices are formed at the Reynolds number above 1000, the flow field is referred to as wake-transition regime, where the secondary vortices with the spanwise wavelength of about one cylinder diameter appear (Williamson, 1996). Considering that three-dimensionality is introduced in the near-wake region by some flow instability, it is of great importance to observe the topological features of the structures in this region.

Before analyzing the flow topology, the trajectory of a vortex shed from the cylinder should be well established. Specific definitions of a vortex have been recently proposed. Lugt (1979) defined a vortex as a 'multitude of material particles rotating around a common center'. According to Chong *et al.* (1990), a vortex is a region of complex eigenvalues of ∇u, while Hunt *et al.* (1988) identified a vortex as a region containing both a positive second invariant of ∇u and low pressure. Jeong & Hussain (1995) proposed a definition of a vortex in an incompressible flow in terms of the eigenvalues of the symmetric tensor $S^2 + \Omega^2$, where S and Ω are the symmetric and antisymmetric parts of the velocity gradient tensor ∇u, respectively. This definition captures the pressure minimum in a plane perpendicular to the vortex axis at high Reynolds numbers, and also accurately defines vortex cores at low Reynolds numbers, unlike the pressure-minimum criterion. On the other hand, Cantwell & Coles (1983) and Sung & Yoo (2003) determined the vortex center from the centroid of the vorticity, which is an integrated value and a more robust definition for experimental analysis. Nevertheless, it has a limit in identifying a vortex in the recirculation region because there can not be found a single and distinct vortex in terms of the spanwise vorticity distribution. Thus, in the present study, the vortex center is captured by a careful examination of the imaginary eigenvalues of the velocity gradient tensor in the early stages of the formation process, and the trajectory is matched with that evaluated from the centroid of the vorticity on the outside.

For high-definition analysis, a critical-point concept has been often used in previous works. Critical points are the points in the flow field where the velocity is zero relative to an appropriate observer and the streamline slope is indeterminate. Asymptotically exact solutions of the Navier-Stokes and continuity equations can be derived close to the critical points, which give a number of standard flow patterns. Perry & Chong (1987) and Chong *et al.* (1990) made a systematic classification of critical points which might be found in two- and three-dimensional flow fields. The critical points are defined from the flow patterns viewed in a frame of reference translating with the vortices (Zhou & Antonia, 1994). Thus, the streamline patterns are sensitive to the choice of the velocity of the observer so that one topological pattern may change into another depending on the choice of the convection velocity (Perry & Chong, 1987). However, it is difficult to define the most appropriate convection velocity precisely, since the structures are developing with streamwise distance and different parts of the pattern are being convected at different velocities. By following the approach of Cantwell & Coles (1983), in the present study, the convection velocity is obtained by the displacement history of the vortex center for the Kármán vortex in the near wake.

The objective of the present study is to investigate the topological features and vortex dynamics of the near wake behind a circular cylinder in the steady and oscillatory incident flows. The two-dimensional flow fields in the wake-transition regime at a Reynolds number 360 are measured by a time-resolved PIV system. The flow oscillation is generated with twice the natural shedding frequency, which may result in vortex lock-on and lead to a substantial increase in the oscillatory lift and drag forces. In order to analyze the flow topology, first of all, the vortex trajectories are clearly drawn in the near wake including the vortex formation region. Then, the sectional topologies in the moving frame of reference are discussed. In the wake of a bluff body, vortex shedding has an influence on the physical parameters such as separation and reattachment points and the Reynolds stresses. Thus, the mean separation streamline (wake bubble) is considered to see how it is related to the Reynolds stress distributions and the vortex trajectory. These flow properties are also compared with those of the lock-on flow and the change of vortex dynamics from natural state to locked one are interpreted on the basis of the phase-averaged behaviors.

2. Experimental Arrangement

Experiments are conducted in a closed-cycle water tunnel with the size of the test section, which is 15 cm wide, 10 cm high and 100 cm long. A circular cylinder is made of an acrylic plastic bar and placed horizontally across the test section, which is 5 mm in diameter *D*, giving an aspect ratio of 30. The coordinate system is defined such that the origin is located at the center of the circular cylinder with *x*, *y* and *z* representing the streamwise, cross-stream (transverse) and spanwise directions, respectively. The flow oscillation is produced by rotating a set of three shutters that are located at the downstream end of the working section (Armstrong *et al.*, 1986). Each of the shutters comprises pairs of rectangular steel plates that fit into three vertical stainless-steel rods which are spaced at equal distances. The shutters are rotated in phase by a variable AC servo-motor through a timing-belt drive. The frequency of the velocity oscillation f_o is twice that of the shutters since the time-varying blockage imposed on the flow by the shutters, repeats itself every half turn of the shutters. This system for producing an oscillatory flow is similar to that described by Armstrong *et al.* (1986). The measurement plane is one *x*-*y* plane as shown in Fig. 1, where the field of view is $0 < x < 4.6\ D$ and $-2\ D < y < 2\ D$.

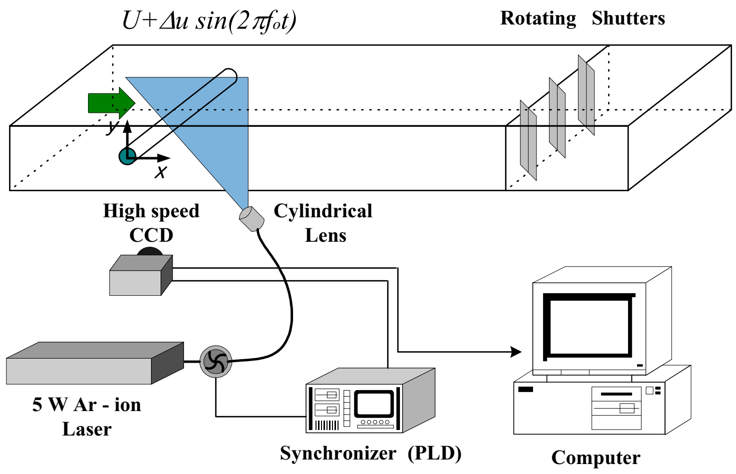

Fig. 1. Experimental setup for the time-resolved PIV measurement. The oscillating flow is produced by rotating shutters at the downstream end of the working section.

To measure the velocity field in the wake of a circular cylinder, hollow glass particles with 10-μm mean diameter and specific weight 1.1 g/cm^3 are used to seed the flow. A time-resolved PIV system is used, where the particles are illuminated by a light sheet less than 1mm in thickness, emitted from a 5-W argon-ion laser (Stabilite 2017, Spectra-Physics) and the scattered light is captured by a high speed CCD camera (Hi-Dcam PCI 2000, NAC). This camera has an 8-bit sensor array of 480 × 420 pixels and can obtain images at a maximum speed of 250 frames/s with full resolution and 2000 frames with partial resolution (160 × 140 pixels). Continuous laser light is chopped by an electro-optic shutter (80X41, DANTEC) with a frequency response up to 50 kHz using a modulator crystal and a polarizer. This shutter can be triggered by a TTL signal and is synchronized with the camera using a PLD (programmable logic device). Velocity vectors are determined by cross-correlation analysis using FFT (Fast Fourier Transform) with 16-pixel × 16-pixel interrogation windows. To enhance the signal-to-noise ratio, window shifting technique is adopted and more detailed information can be found in our previous work (Sung & Yoo, 2001). In the present study, a total of 2048 successive frames are acquired at 250 frames/s for one run, which produces 1024 velocity fields sampled at 125 Hz. This sample frequency is 40 times higher than the vortex shedding frequency obtained in the present application. Four sets of 1024 successive velocity fields are acquired yielding a total of 4096 samples or about 100 shedding cycles. The reproducibility of the instantaneous local velocities is within 3.4% of the free-stream velocity for a 95% confidence limit, and that of ∇u is 0.044/s as it is calculated with 2σ/h, where σ is the standard deviation of the velocity and h is the grid spacing.

In the oscillatory flow at the lock-on state, the uncertainty of the oscillatory flow has been checked in the absence of the cylinder to examine the generation of the stable oscillatory flow field. Due to the nonlinear feature of the fluid dynamics, there are also super-harmonics of the forcing frequency but their magnitudes are relatively small compared with that of the fundamental frequency. The Fourier-series analysis indicates that the second and third harmonics are less than 30% of the fundamental. The oscillation amplitude Δu at a given oscillation frequency is determined from the Fourier-series coefficient at the fundamental frequency. The uncertainty of oscillation amplitude along the y axis for a 95% confidence limit is 5% of average Fourier-series coefficient (Δu_{avg}), i.e., average oscillation amplitude which is 4.7% of mean flow velocity U = 72.4 mm/s. Oscillation amplitudes are generated by changing the oscillation frequency at constant mean free-stream velocity. The non-dimensional oscillation amplitude, $2\Delta u/\omega D$, is 0.03 at the lock-on condition while its threshold for lock-on to occur is about 0.01. It is known that the oscillating amplitude affects the frequency limit of the lock-on (Barbi *et al.*, 1986) but further consideration is not made in the present study. The variations of the free-stream velocity by the presence of the oscillating shutters are less than 1%. The non-dimensional amplitude of the free-stream turbulence is about 0.002, which is too low to affect lock-on structures.

3. Trajectory of Vortex Center for Flow Topological Analysis

To investigate the trajectory of a vortex center, first of all, we should identify the vortex center. There are two possible previous definitions of the vortex center: one is the peak position of the vorticity and the other is the centroid of the vorticity field. The former is easy to realize but may result in high uncertainty, and the latter proposed by Cantwell & Coles (1983) at the Reynolds number 140,000 is used with the centroid evaluated in the x-y plane as follows:

$$\Gamma = \int_A \langle \omega_z \rangle dA$$
$$x_c = \frac{1}{\Gamma}\int_A x\langle \omega_z \rangle dA \qquad (1)$$
$$y_c = \frac{1}{\Gamma}\int_A y\langle \omega_z \rangle dA$$

where Γ is the circulation and A is the integration area which is restricted to the outside of the reverse-flow region ($x/D > 1.7$), since not a single vortex can be found on the inside. The integration in each case is allowed only for values of $\langle\omega_z\rangle/\langle\omega_z\rangle_p \geq 0.5$ to avoid relatively noisy data, where $\langle\omega_z\rangle_p$ is the maximum vorticity in the near-wake region.

However, the centroid method of the vorticity cannot be used in the wake bubble, because a complete vortex cannot be identified from the spanwise vorticity distribution. Therefore, another method using a different definition of vortex is necessary. Recently, a distinct definition of a vortex has been proposed based on Galilean invariants of the velocity gradient tensor (Chong *et al.* (1990), Hunt *et al.* (1988), Melander & Hussain (1993)). Chong *et al.* (1990) used eigenvalues of the velocity gradient tensor ∇u to classify the local streamline pattern around any point in a flow in a reference frame moving with the velocity of that point. They proposed that a vortex core is a region with complex eigenvalues of ∇u, which imply that the local streamline pattern is closed or spiral in a reference frame moving with the point.

Here, we briefly recall the basic concept. The eigenvalues, λ, of ∇u satisfy the characteristic equation of three-dimensional flow as follows:

$$\lambda^3 - P\lambda^2 + Q\lambda - R = 0 \qquad (2)$$

where $P \equiv u_{i,i} = 0$ (incompressible flow), $Q \equiv 1/2({u^2}_{i,i} - u_{i,j}u_{j,i}) = -1/2(u_{i,j}u_{j,i})$ and $R = Det(u_{i,j})$ are the three invariants of ∇u. Complex eigenvalues will occur when the discriminant ($\Delta = (1/3Q)^3 + (1/2R)^2$) is positive. On the other hand, the condition for complex eigenvalues in the two-dimensional flow is that Δ is negative. This concept is used to identify the vortex core at the near field of the cylinder wake, that is, the wake bubble. In the early stages of the formation process, the vortex center can be captured by a careful examination of the complex eigenvalues of the velocity gradient tensor, which has been well established to extract vortices with local circular or spiralling streamlines (Dallmann *et al.* (1991), Chong *et al.* (1990), Mittal & Balachandar (1995)). In the upper part of Fig. 2(a), the trajectories extracted from the two methods are compared. Inside the wake bubble, a vortex undergoes the process of formation and there exists a high vorticity region in the shear layer, which is not a vortex but causes the centroid of vorticity to be shifted towards the shear layer. Thus, it is necessary to apply complex eigenvalue definition. Downstream of that region, whereas, the centroid of the vorticity is more plausible to be defined as the vortex center since it is an integrated value and gives robust results compared with the differential quantities of velocity gradient. The resultant trajectory obtained by matching the respective trajectories in the two regions is plotted in the lower part of Fig. 2(a).

For the topological analysis on the flow structure, we are to observe the sectional flow fields regarding critical points in the frame of reference moving at the convection velocity of the vortical structure in the *x-y* plane. A detailed description of the critical point theory can be found in Perry & Chong (1987) and Chong *et al.* (1990). The critical point is defined as a point where the streamline slope is indeterminate and the velocity at this point is zero. The local flow pattern around the point is governed by the velocity gradient tensor. The vortex center is also one of the critical points.

In Fig. 2(b), the sectional streamlines in a moving frame of reference are shown at phase 0° in the *x-y* plane. The reference signal for phase-average is extracted at (x/D, y/D) = (1.5, 0.5) and the phase 0° denotes peak of the streamwise velocity at that point. The convection velocity in the near wake varies with the streamwise location of the vortices so that it can be represented as a function of time. In the far wake of a bluff body, the convection velocity of the coherent structure is nearly constant but it is not so in the near wake because the structures are being developed in the streamwise direction. Therefore, in the present study, the time-varying convection velocities in the near wake are determined by differentiating the locus of the vortex center given in Fig. 2(a). In the streamline pattern of Fig. 2(b), some critical points such as focus and saddle are detected, which would not be clearly seen in a fixed frame of reference.

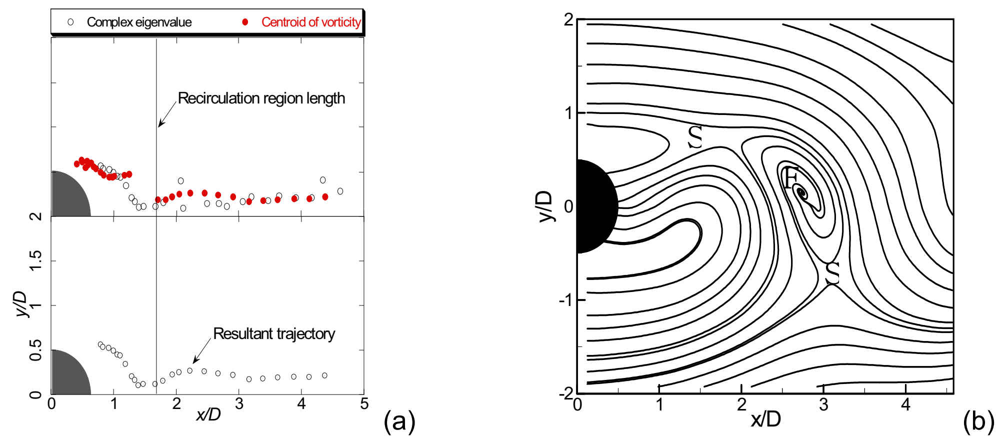

Fig. 2 (a) Trajectories of the vortex center obtained by using the centroid of the vorticity in conjunction with the complex eigenvalue method. (b) Flow field in the *x-y* plane at phase 0° viewed from a moving frame of reference: S, saddle; F, focus.

4. Vortex Dynamics in Steady and Oscillatory Flows

In this Section, vortex dynamics in steady and oscillatory flows is discussed in terms of the trajectory of the vortex center, the mean separation streamline (wake bubble) and Reynolds stresses. The steady flow induces natural shedding, while the oscillatory flow gives rise to lock-on when the oscillating frequency (f_o) is about twice the natural shedding frequency (f_n), i.e., when $f_o / f_n = 2.0$. If the lock-on takes place, the shedding frequency becomes half the oscillatory forcing frequency. Thus, the oscillatory flow with $f_o / f_n = 2.0$ and steady flow lead to the same shedding frequency. However, there is a lot of difference in the vortex dynamics as shown in Fig. 3 since one is natural and the other is forced. The overall results for the natural shedding case are much similar to those of DNS by Balachandar *et al.* (1997) at $Re = 300$, which verifies well the results of the present study.

The trajectory of the vortex center, as mentioned earlier, is extracted by evaluating complex eigenvalues of the velocity gradient tensor in the wake bubble and identifying the centroids of the vorticity in the downstream region. The trajectory, solid-circle symbols in Fig. 3, is acquired at the upper side, and the data at the lower side are mirror images due to symmetry of the cylinder wake.

Each symbol represents the position of the vortex center at 1/16 of the shedding period and the distance between neighboring symbols provides the convection velocities of the vortices. The mean separation streamlines are also presented in Fig. 3, which describes the boundary of the recirculation region or wake bubble.

To obtain this streamline, the following procedure is performed: The first step is to search for the separation point by tracing streams from 90° to 180° with one degree interval. The second is to link the streamline to the reattachment point since this separation streamline does not exactly go through that point due to the insufficient grid resolution of the experiment. Thus, the separation streamline is cut at inflection point and then linearly connected to the reattachment point.

As shown in Fig. 3, for the natural shedding and lock-on cases, the Kármán vortex gradually grows up in the shear layer and moves towards the wake centerline. Just after passing through the wake bubble, it starts to move fast. As it goes downstream, it gets away from the centerline slightly and then turns to the centerline again with acceleration. Finally, it moves parallel to the x-axis. However, there are two significant differences in the trajectories. One is that in the lock-on case, the paths of the vortices shed at the upper and lower sides meet together at the reattachment point, whereas in the natural shedding case, the closest point of the paths lies inside the wake bubble without meeting together. The other is, far downstream, the lock-on makes the vortex remain much closer to the centerline. Thus, it appears that the upper and lower vortex streets are merged into a line. By the vortex lock-on, the streamwise length of the wake bubble is shorter than that of the natural shedding case and the separation point moves slightly downstream.

Since the Reynolds normal and shear stresses play important roles in the analysis of vortex dynamics, their distributions are overlapped with the boundary of the wake bubble and the trajectory of the vortex center for natural shedding (Figs. 3(a) - 3(c)) and lock-on (Figs. 3(d) - 3(f)) states. Here, the same contour levels in the two states are used for $<\overline{u'u'}>$, $<\overline{u'v'}>$ and $<\overline{v'v'}>$, respectively. On the whole, the intensities of Reynolds stress components are much more increased by the lock-on, which might be closely related to the increase of drag and lift forces. The maxima of $<\overline{u'u'}>$, $<\overline{u'v'}>$ and $<\overline{v'v'}>$ in the lock-on state are 59%, 25% and 24% higher than those in the natural shedding state, respectively. Regarding the Reynolds streamwise normal stress $<\overline{u'u'}>$ in Figs. 3(a) and 3(d), its distribution has commonly a twin-peak pattern. While the peak is located on the mean separation streamline in the natural shedding case, the peak position in the lock-on case is found downstream of the separation streamline. Meanwhile, the Reynolds shear stress $<\overline{u'v'}>$ in Figs. 3(b) and 3(e) shows the peak-and-valley patterns for the two cases. Inside the wake bubble, $<\overline{u'v'}>$ is positive in the upper side and negative in the lower side, changing the sign outside of the wake bubble. The outstanding feature of the distribution is that the peak-and-valley pattern is exactly divided by the mean separation streamline. It is a good evidence for the perfect synchronization of vortices to the oscillatory flow. Finally, the Reynolds cross-stream normal stress $<\overline{v'v'}>$ in Figs. 3(c) and 3(f) reveals one peak pattern on the wake centerline. When the lock-on happens, a very steep gradient of the stress exists right backside of the cylinder. It means that strong upward and downward motions are induced in this area during the vortex shedding process.

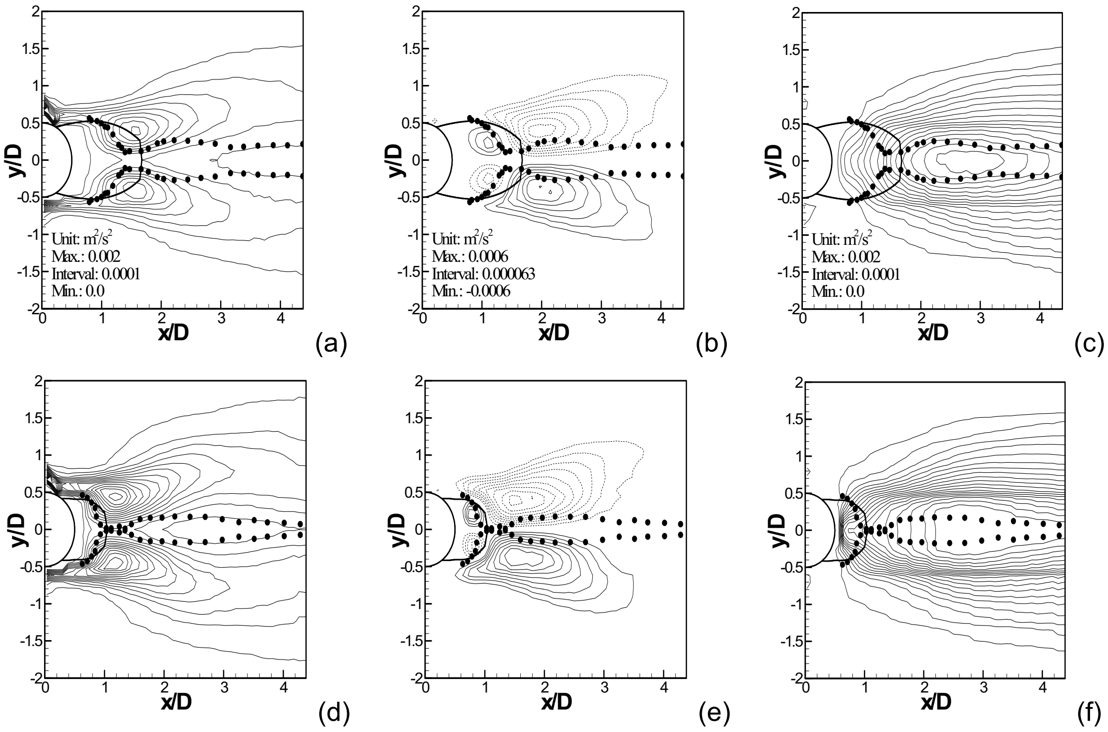

Fig. 3 Coherent Reynolds stress distribution in the wake of a circular cylinder: (a)-(c) natural shedding flow, (d)-(f) lock-on flow; (a) and (d) $<\overline{u'u'}>$, (b) and (e) $<\overline{u'v'}>$, (c) and (f) $<\overline{v'v'}>$

To sum up the effect of the lock-on flow on the vortex dynamics, it can be said that the trajectory of the vortex center passes through the reattachment point and approaches the wake centerline in the far wake. The Reynolds stresses become stronger and their dispositions match well with the shortened wake bubble showing the perfect synchronization of shedding in the near field.

5. Conclusion

The velocity fields in the near wake behind a circular cylinder at the Reynolds number 360 are measured by a time-resolved PIV system on an x-y plane. To investigate the topological features and vortex dynamics in the steady and oscillatory incident flows, we examined the trajectory of the vortex center, critical point, mean separation streamline and distribution of the Reynolds stresses. First of all, the vortex center is captured by a careful examination of the imaginary eigenvalues of the velocity gradient tensor in the early stages of the formation process, and the trajectory is matched with that evaluated from the centroid of the vorticity on the outside. The trajectory of the vortex center gives a good representation of the motion of the spanwise vortices during their evolution. In order to examine the flow topology in a moving frame of reference, the convection velocity is derived from the trajectory of the vortex center in the x-y plane. The resultant flow field viewed from a moving frame of reference has several critical points. The Reynolds stress distribution is evaluated together with mean separation streamline and the trajectory of the vortex center to compare the lock-on state with the natural shedding case. Special features of the lock-on state are that the wake bubble is substantially shortened and that the trajectories of the vortex shed in the upper and lower sides passes through the reattachment point meeting together at this point. Farther downstream, the vortex streets gather around the wake centerline. The Reynolds stresses seem to be much stronger and synchronized perfectly to the oscillatory forcing flow in the near field, which causes increased lift and drag forces.

References

Armstrong, B. J., Barnes, F. H. and Grant, I., The Effect of a Perturbation on the Flow Over a Bluff Cylinder, Phys. Fluids, 29-7 (1986), 2095.
Balachandar, S., Mittal, R. and Najjar, F. M., Properties of the Mean Recirculation Region in the Wakes of Two-Dimensional Bluff Bodies, J. Fluid Mech., 351 (1997), 167.
Barbi, C., Favier, D. P., Maresca, C. A. and Telionis, D. P., Vortex Shedding and Lock-On of a Circular Cylinder in Oscillatory Flow, J. Fluid Mech., 170 (1986), 527.
Cantwell, B. and Coles, D., An Experimental Study of Entrainment and Transport in the Turbulent Near Wake of a Circular Cylinder, J. Fluid Mech., 136 (1983), 321.
Chong, M. S., Perry, A. E. and Cantwell, B. J., A General Classification of Three-Dimensional Flow Fields, Phys. Fluids A, 2-5 (1990), 765.
Dallmann, U., Hilgenstock, A., Riedelbauch, S., Schulte-Werning, B. and Vollmers, H., On the Footprints of Three-Dimensional Separated Vortex Flows Around Blunt Bodies, AGARD CP-494 (1991).
Hunt, J. C. R., Wray, A. A. and Moin, P., Eddies, Stream, and Convergence Zones in Turbulent Flows, Center for Turbulence Research Report CTR-S88 (1988), 193.
Hussain, F. and Melander, M. V., Understanding Turbulence Via Vortex Dynamics, In The Lumley Symposium: Studies in Turbulence, Springer, (1991), 157.
Jeong, J. and Hussain, F., On the Identification of a Vortex, J. Fluid Mech., 285 (1995), 69.
Lugt, H. J., The Dilemma of Defining a Vortex, In Recent Developments in Theoretical and Experimental Fluid Mechanics (ed. U. Müller, K. G. Roesner and B. Schmidt), Springer, (1979), 309.
Melander, M. and Hussain, F., Polarized Vorticity Dynamics on a Vortex Column, Phys. Fluids A, 5 (1993), 1992.
Mittal, R. and Balachandar, S., Generation of Streamwise Vortical Structures in Bluff Body Wakes, Phys. Rev. Lett., 75 (1995), 1300.
Perry, A. E. and Chong, M. S., A Description of Eddying Motions and Flow Patterns Using Critical-Point Concepts, Ann. Rev. Fluid Mech., 19 (1987), 125.
Sung, J. and Yoo, J. Y., Three-Dimensional Phase Averaging of Time-Resolved PIV Measurement Data, Meas. Sci. Technol., 12-6 (2001), 655.
Sung, J. and Yoo, J. Y., Near-Wake Vortex Motions Behind a Circular Cylinder at low Reynolds Number. J. Fluids Struct., 17 (2003), 261.
Williamson, C. H. K., Three-Dimensional Wake Transition, J. Fluid Mech., 328 (1996), 345.
Zhou, Y. and Antonia, R. A., Critical Points in a Turbulent Near Wake, J. Fluid Mech., 275 (1994), 59.

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