PIV EXPERIMENT ON A 3-D WAKE OF A CIRCULAR CYLINDER IN A CROSS FLOW

Kazuo Ohmi*, Seunghee Jeon**, Achyut Sapkota**
*Osaka Sangyo University, 3-1-1 Nakagaito, Daito, Osaka 574-8530, Japan,
**Graduate School - Osaka Sangyo University, Osaka 574-8530, Japan,
Corresponding author: ohmi@ise.osaka-sandai.ac.jp

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Abstract

Three-dimensional behavior of the low Reynolds number wake of a circular cylinder in a cross flow has been examined by 3-D PIV experiment in a circulating water channel. The wake is observed in a measurement plane fixed normal or parallel to the cylinder axis and distribution of velocity in three Cartesian components and contours of vorticity are obtained on this plane. For time-series data processing of PIV velocity fields, the sampling rate of PIV image pairs is determined with 10 % difference from the predominant wake frequency measured with Laser Doppler velocimetry. The main objective of the study is to investigate the 3-D characteristic behaviors of vortex wakes in the lower range of Reynolds numbers with laminar flow separation.

1 Introduction

It is widely known that a two-dimensional cylindrical body placed in a uniform cross flow produces a periodically fluctuating wake composed of two parallel rows vortices in staggered arrangement, or Karman vortex streets. And in this wake, as the cross flow velocity is increased from a low level, small turbulence is produced progressively along the shear layers and at last the whole wake grows into a fully turbulent flow while retaining overall structure of Karman vortex streets in a statistical viewpoint. And this process inevitably accompanies development of three-dimensional behavior in the vortex wake. If the cross flow Reynolds number is small (say 100) and turbulence level of the vortex wake is low enough, it is generally understood that the three-dimensional nature of the Karman vortex flow is only recognized in some limited portions, for instance in the vicinity of the two ends of the cylinder span.

However in a couple of past decades, it has been gradually revealed [1]-[7] that even in such a low Re-number flow there exist a certain extent of three-dimensional motions along the whole span of the cylinder and that this flow behavior is closely related to irregular variation in the Strouhal-Reynolds relationship originally observed by Roshko [8] in a wind tunnel experiment as well as to the relatively well-known arguments by Tritton and Gaster [9]-[12] on the vortex shedding mode with respect to Reynolds number. But most of these earlier researches are based on qualitative observation of visualized fluid flows or a limited extent of quantitative data without support from whole-field velocity measurement. In the present study, therefore, 3-D structure of the vortex wake of a circular cylinder is investigated by 3-D PIV experiment in a small-size circulating water channel.

2 Experimental setup

The flow visualization and PIV experiment is conducted in a circulating water channel with a test section of 175x175x950 mm³ capacity. The test cylinder with a relatively low aspect ratio (19 mm diameter and 175 mm span length) is fixed horizontally or vertically at the middle height or depth of the channel test section. The PIV measurement plane is fixed vertically in the rear of the cylinder and along the centerline of the channel width. Therefore this measurement plane is parallel or normal to the cylinder axis according to the two positions of the cylinder as
shown in Fig.1. Two stereoscopic cameras are oriented inversely slantwise with respect to the measurement plane and arranged in the standard Scheimpflug arrangement. The camera images are calibrated in advance by using a dot pattern calibrator placed in the measurement section to cover the whole measurement field. Thus all the recorded particle images are converted into real scale images prior to reconstructing the three velocity components on this plane.

The 3-D PIV system used here is basically composed of TSI products including two 1.3k Sensicam cameras, one dual-CPU Windows PC with two frame grabbers and a 2-channel TTL pulse board, one double-pulse Nd:YAG laser (30mJ/pulse) with cylindrical lens optics and a digital delay pulse generator. These components are all controlled by the TSI Insight software which enables synchronous image capturing at given time intervals, cross correlation particle displacement analysis in each of the two camera frames and finally reconstruction of 3-D particle displacement from the two synchronous sets of 2-D displacement results.

In the present experiment, the cross flow Reynolds number is fixed at 100 or 200 with the free stream velocity of about 5.5 to 11.0 mm/s. The free stream turbulence level is lower than 1.5% in this range of mean flow velocity. The cylinder aspect ratio is fixed at a low value of 9.21 throughout the experiment because the 3-D effects from the ends of the cylinder span are expected to intervene with the inherent 3-D structure of the cylinder wake. Nevertheless the objective of the study is not limited to the short cylinder cases. In a series of currently ongoing PIV experiments, the long cylinder cases are extensively investigated for more general views.

3 PIV results

3.1 Horizontal cylinder arrangement

The PIV results of this cylinder arrangement illustrate a typical scenario of classical Karman vortex shedding from a cylindrical bluff body as shown in Figs.2 and 3. In both of these figures, (b) gives instantaneous x-y vorticity contours in the cylinder wake, where positive and negative vorticity peaks are placed in a regular staggered arrangement. In the same figures, (a) represents an instantaneous 3-D velocity distribution at the same instant as in (b). The black arrows show the in-plane velocity while the color gradation the magnitude of the out-of-plane velocity. It is clearly seen that the peak regions of the out-of-plane velocity correspond to that of x-y vorticity. This means that the vortices generated behind a relatively short-span cylinder travel downstream with a certain extent of axial velocity, probably because each vortex core is stretched toward the ends of the cylinder span. If comparing Figs.2 and 3, the correlation between the out-of-plane velocity and the in-plane vorticity is increased in the higher Re number case (=200). Locations of both peaks are more clearly overlapping and the sign of the two parameters at these peaks is more regularly correlated. Another observation from the comparison of these two figures is that the wake turbulence, shown in (c), is spread out wider and more downstream in the higher Re number case. Corresponding to this, the production of Reynolds shear stress is increased in the near wake region.
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Fig. 2 Horizontal cylinder PIV results at Re=100

Fig. 3 Horizontal cylinder PIV results at Re=200
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Fig. 4 Vertical cylinder PIV results at Re=100

Fig. 5 Vertical cylinder PIV results at Re=200
3.2 Vertical cylinder arrangement

The PIV results from the vertical cylinder arrangement are given in Figures 4 through 6. It should be noted here that the measurement coordinate system is relative to the directions of the cross flow and of the cylinder span regardless of the apparent cylinder arrangement. So z-axis is always oriented to the cylinder span as shown in Fig.1 Bearing this in mind, the 3-D velocity profiles in Fig.4 (a) to (c) and Fig.5 (a) to (c) show the velocity distribution in x-z plane and not in x-y plane as depicted near the graph axis. In three velocity profiles, again, the black arrows show the in-plane velocity while the color contour gradation indicates the magnitude of out-of-plane velocity. And (a) through (c) represent different instants of the vortex wake side view. If Re=100 (Fig.4), the vortex core is almost parallel to the cylinder axis but there appears sometimes vortex finger as pointed out earlier by Gerrard [1] or spanwise vortex cell structure as reported by Tritton [11] as well as by Williamson [5]. However if Re=200 (Fig.5), the vortex core is seen often slantwise and the direction of slant is variable with the passage of time. There seems to be no apparent slant angle with respect to the cylinder axis. In addition to this, the vortex core itself is more shortly cell structured than the precedent case. And at some instants, for instance Fig.5 (c), there comes out vortex splitting as reported by Eisenlohr and Eckelmann [7].

The total turbulence level distribution is given in Figs. 4 (d) and 5 (d), in which the higher Re number case shows clearer slant of the local maxima of turbulence production. At the same time, the higher Re number case observes more energetic turbulence production in the near wake region. Fig.6 illustrates time-averaged 3-D velocity profile at Re=200. This figure as well as Fig.5 (c) indicates that the mean slant angle of the vortex core at this higher Re number is inclined to left in x-z plane.

4 Conclusions

3-D behavior of the low Reynolds number wake of a circular cylinder was examined by 3-D PIV experiment in a circulating water channel. From the PIV results it was shown that various types of 3-D vortex motions are observable even at the lower Reynolds number of 100. In these 3-D vortex motions are included streamwise vortex fingers, spanwise vortex core cells and vortex splitting.

References

