Journal of Fluids and Structures (1997) **11,** 617–626

THE WAKE OF AN ORBITING CYLINDER

J. Wu
CSIRO Division of Building, Construction and Engineering, Highett, Victoria, Australia

AND

J. Sheridan
Department of Mechanical Engineering, Monash University, Clayton, Victoria, Australia

(Received 16 December 1996 and in revised form 11 June 1997)

Preliminary results are presented for the flow behind a circular cylinder orbiting about a vertical axis inside a tank. The wake was investigated experimentally using image de-rotation and particle image velocimetry (PIV). It was found that the vortex shedding was perturbed by its own wake and, as a result, showed characteristics distinctively different from the normal vortex shedding behind a stationary cylinder. The vortex structures formed behind the orbiting cylinder include the classical Kármán vortices and regular/irregular small-scale shear layer vortices. The former are frequently overwhelmed by the latter. The formation length of the Kármán vortices is shown to be substantially smaller than in the wake of a stationary cylinder. PIV measurement shows that there is a reduction in the circulation of the vortices in the near wake.

1. INTRODUCTION

The primary motivation of this study was to investigate the flow behind an orbiting circular cylinder inside a vessel, as shown schematically in Figure 1. Compared with the well studied case of flow past a stationary cylinder, a major difference in the present wake development process is that the cylinder constantly moves through its own wake. In this respect the wake has some similarities to the wake of oscillating cylinders without mean flow, as studied by Williamson (1985). As in that case, the near wake vortex shedding is perturbed by its far wake, here at a distance $2\pi R$ downstream of the cylinder, where R is the distance from the cylinder centre to the rotational axis.

The wake of a circular cylinder is of great interest in fluid dynamics because of the development of many distinctive flow structures (Wei & Smith 1986; Williamson 1988; Wu *et al*. 1996a, b) which prove to be illuminating for fluid mechanics researchers, and because it provides a model useful in the study of more complicated industrial fluid processes. Many papers have been published since the turn of this century concerned with different aspects of cylinder wake flows; readers are referred to the comprehensive reviews by Coutanceau & Defaye (1991), Roshko (1993) and Williamson (1996).

Chaplin (1988) has examined planar oscillatory flows in which a cylinder moves in an orbit without rotation in an effectively infinite fluid. However, to the authors' knowledge, the flow behind a cylinder orbiting in a circular path, while also rotating within a constrained fluid, has not been reported in the literature. [The authors are, however, aware of work by Monkewitz *et al*. (1996) which examines the wake of an orbiting cylinder but with its axis orthogonal to that of the present study.] The objective of the present work is therefore to characterize the fluid mechanics of this

0889–9746/97/060617 + 10 $25.00/fl1970099

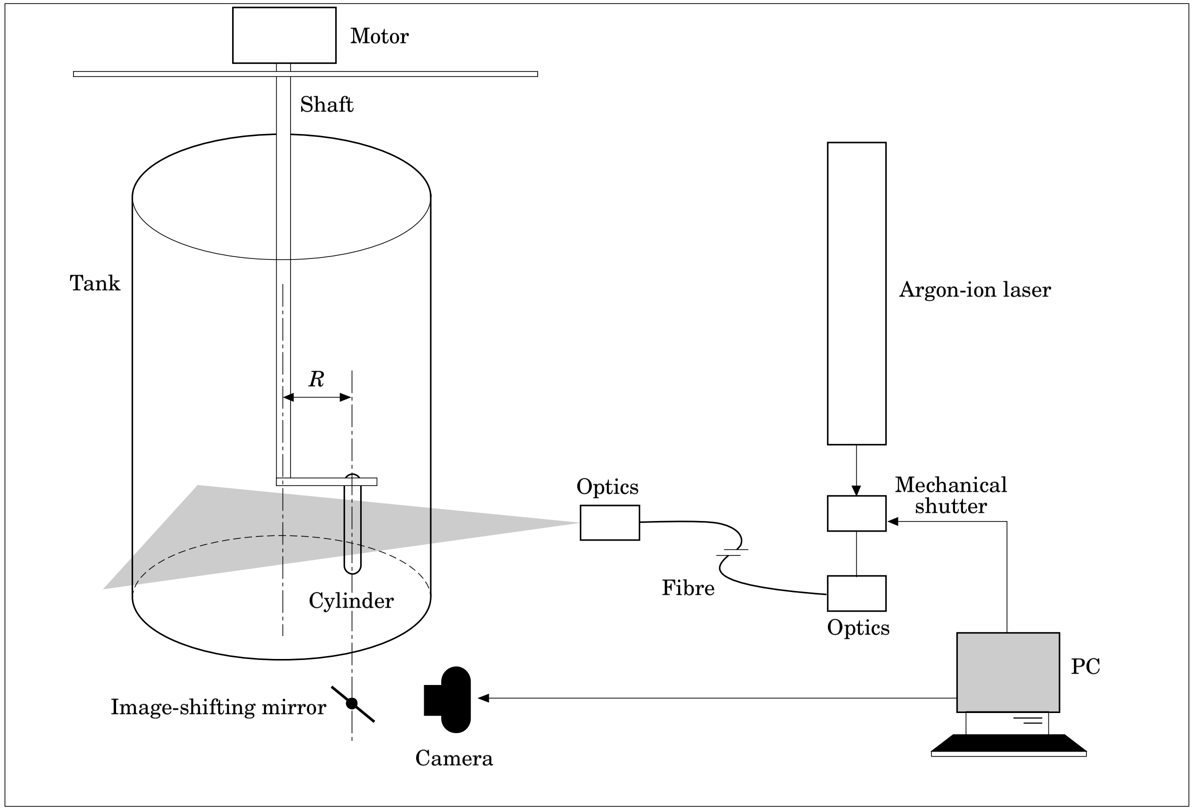

Figure 1. Experimental setup includes a circular cylinder mounted on a rotating arm inside a circular-shaped tank, with water used as fluid. The PIV image system includes a 8 W Spectral Physics Argon-ion laser, a Nikon camera and an image-shifting mirror, all controlled by a 486 personal computer.

rather special cylinder wake. There is also an industrial application of this flow which relates to fluid mixing by impellers in tanks. It is known that vortices shed from a rotating blade influence the performance and control of many important processes, e.g. gas/liquid mixing (Rigby & Evans 1996).

A related field to which this study may have relevance is the investigation of the influence of freestream turbulence on wake development. Niemann & Holscher (1990) have discussed how freestream turbulence alters the laminar to turbulent transition in separated shear layers; this in turn influences the drag and pressure distribution. For the case studied here, it is anticipated that the highly perturbed upstream flows may influence the wake development behind the orbiting cylinder.

2. EXPERIMENTAL APPARATUS AND METHOD

The experimental arrangement is as shown in Figure 1. An acrylic, cylindrical tank of 390 mm in diameter and contained within an outer square-section viewing tank had a central shaft on which there was a rotating arm with a cylinder fixed, its axis being parallel to that of the tank. The cylinder was made from acrylic, 12·7 mm in diameter and 244 mm long. Its position on the rotating shaft was adjustable, allowing different radii of orbit of the cylinder to be examined. A three-phase motor with variable frequency drive was used to drive the shaft; the range of angular speeds being 0–70 r.p.m.

The flow could be observed in the plane of rotation by viewing through the tank base through a mirror placed at 45 degrees to the tank axis. Clearly, of central interest in observing this flow was how it compared with the well known and well-studied Kármán vortex street. To make such a comparison it is desirable to be able to view the orbiting cylinder in a frame of reference fixed to the cylinder. A new experimental technique, developed by Wu *et al*. (1996c), was used to do this. In essence, the device consists of the 'dove'-shaped prism shown in Figure 2, which rotates at half the cylinder speed. The rotation of the prism introduces a bias rotational velocity to the image, such that the view through the prism is equivalent to what would be seen in the frame of reference fixed to the orbiting cylinder. Thus, this 'de-rotation' technique permits viewing of the cylinder wake in such a way that a direct comparison is possible with that of fixed cylinders.

Both the flow visualisations and PIV measurements were illuminated by a light sheet generated by a Spectra Physics 8 W argon-ion laser. The flow was seeded with silver-coated glass particles having a mean size of 14 μm. An electro-mechanical shutter, installed between the laser and the fibre-optic coupler used to carry the light to the experiment, pulsed the laser light so that multiple images of each particle were recorded in each frame of film.

For the PIV measurements, a Nikon camera was used to record multiply exposed particle images on Kodak Tmax 400, 35 mm film. A rotating mirror was used to introduce bias velocity so that directional ambiguity and the dynamic range limitation inherent in an auto-correlation PIV system were overcome. The films were then digitized into digital images at a resolution of 3700 by 2500 pixels using a Polaroid scanner. The digital particle images were then processed on a PC using a custom-developed software.

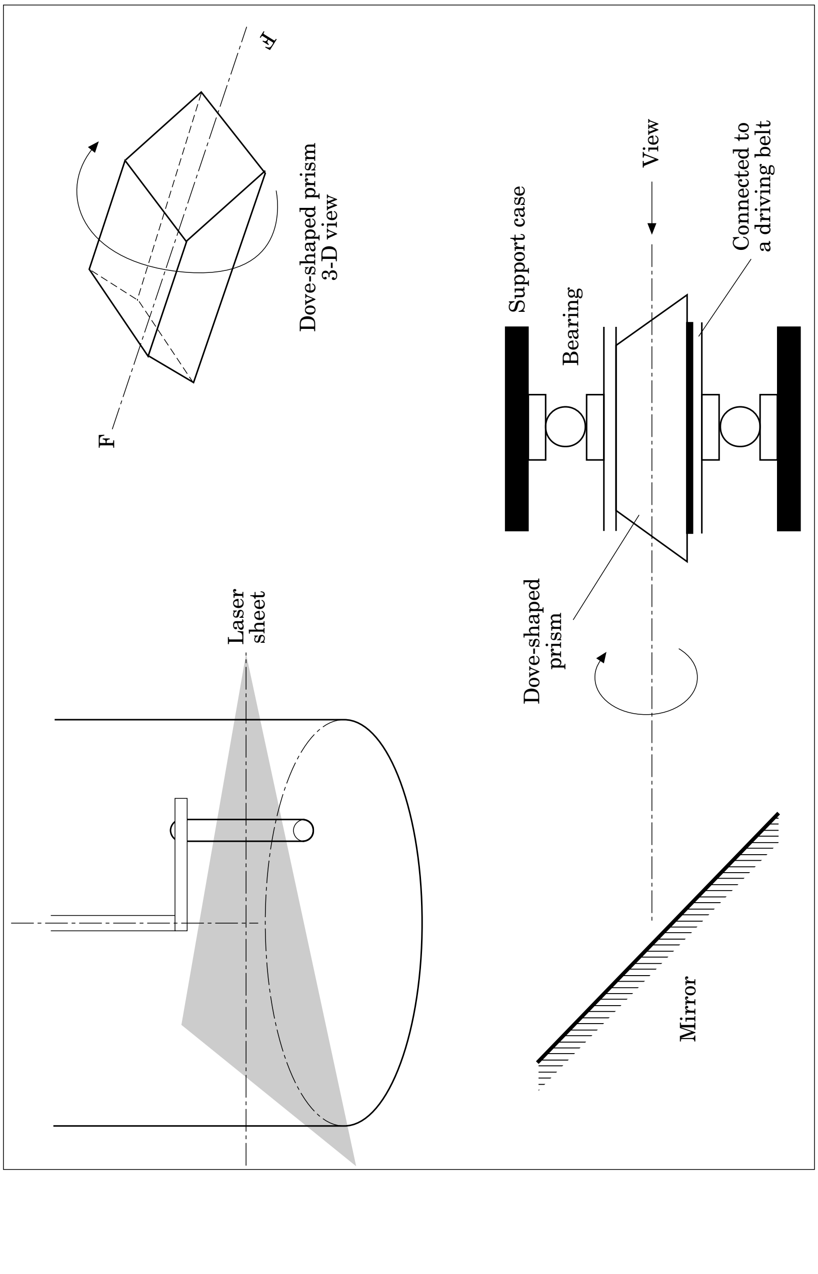

Figure 2. Image de-rotator, the dove-shaped prism is 30×30 mm in cross-section and is mounted inside a bearing. The rotation of the prism is driven by a DC variable speed motor through a gear box and belt.

3. RESULTS AND DISCUSSION

3.1. A Switching Mechanism

Using the image de-rotation device, it is possible to observe the flow past the orbiting cylinder in the rotating frame of reference in real time. Based on these observations, two distinctively different vortex shedding patterns appear to exist. Figure 3(a, b) shows two typical flow patterns recorded in the rotating frame of reference at Reynolds number of 1600, based on cylinder diameter and the cylinder centreline velocity, and at a cylinder radius $R = 69$ mm. In Figure 3(a), Kármán vortices are seen developing behind the cylinder, similar to those observed in the wake of a stationary cylinder. However, the vortices were found to unstable, at times breaking down into small-scale vortices, as shown in Figure 3(b).

To evaluate the statistical behaviour of the two flow patterns, 30 images were taken of the near wake. The distance between discernible vortices with the same sense of rotation was measured. Figure 4 shows the probability density function (P.D.F.) of the streamwise wavelength. Two peaks appear to exist: one is at $\lambda/D \approx 3$ and the other at $\lambda/D \approx 0{\cdot}75$, where λ is the streamwise wavelength and D is the diameter. It is clear that the longer wavelength corresponds to the large scale of the Kármán vortices.

The smaller peak warrants further discussion. It has been established that small-scale shear layer vortices develop in the near-wake region prior to the formation of Kármán vortices. These vortices are similar in nature to those resulting from the Kelvin-Helmholtz (KH) instability in free shear layers (Bloor 1964; Wei & Smith 1986; Kourta *et al*. 1987; Sheridan *et al*. 1992; Williamson *et al.* 1995).

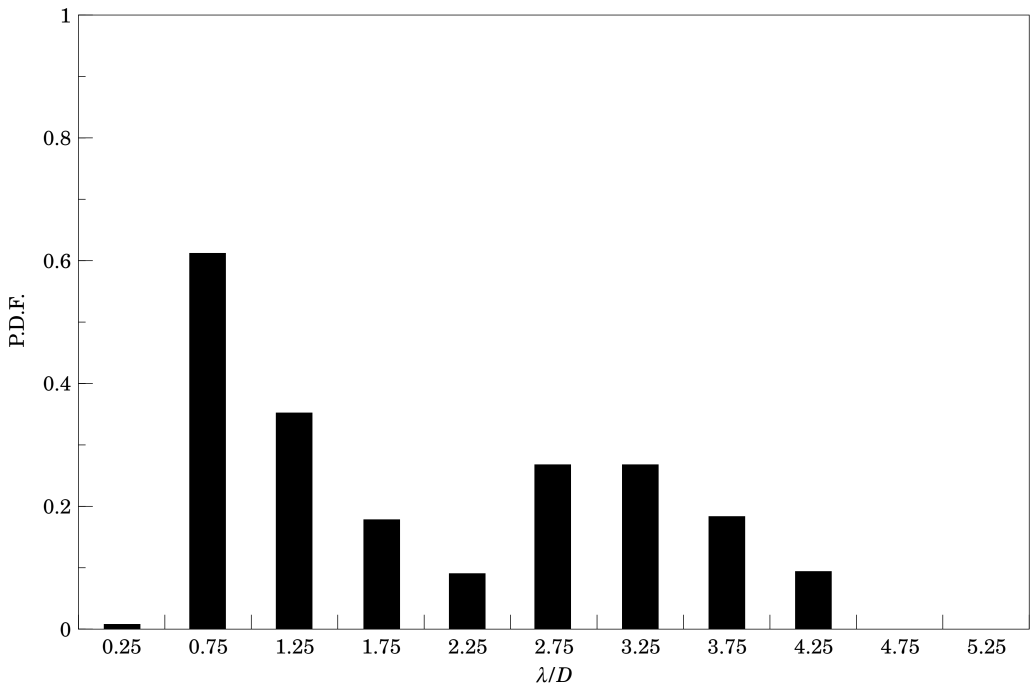

Figure 4. P.D.F. of the streamwise wavelength of the vortices in the near-wake region. Results were based on 30 flow visualisation images. Impeller speed was 17·4 r.p.m. and the radius of the cylinder centre to the rotating axis was 69 mm.

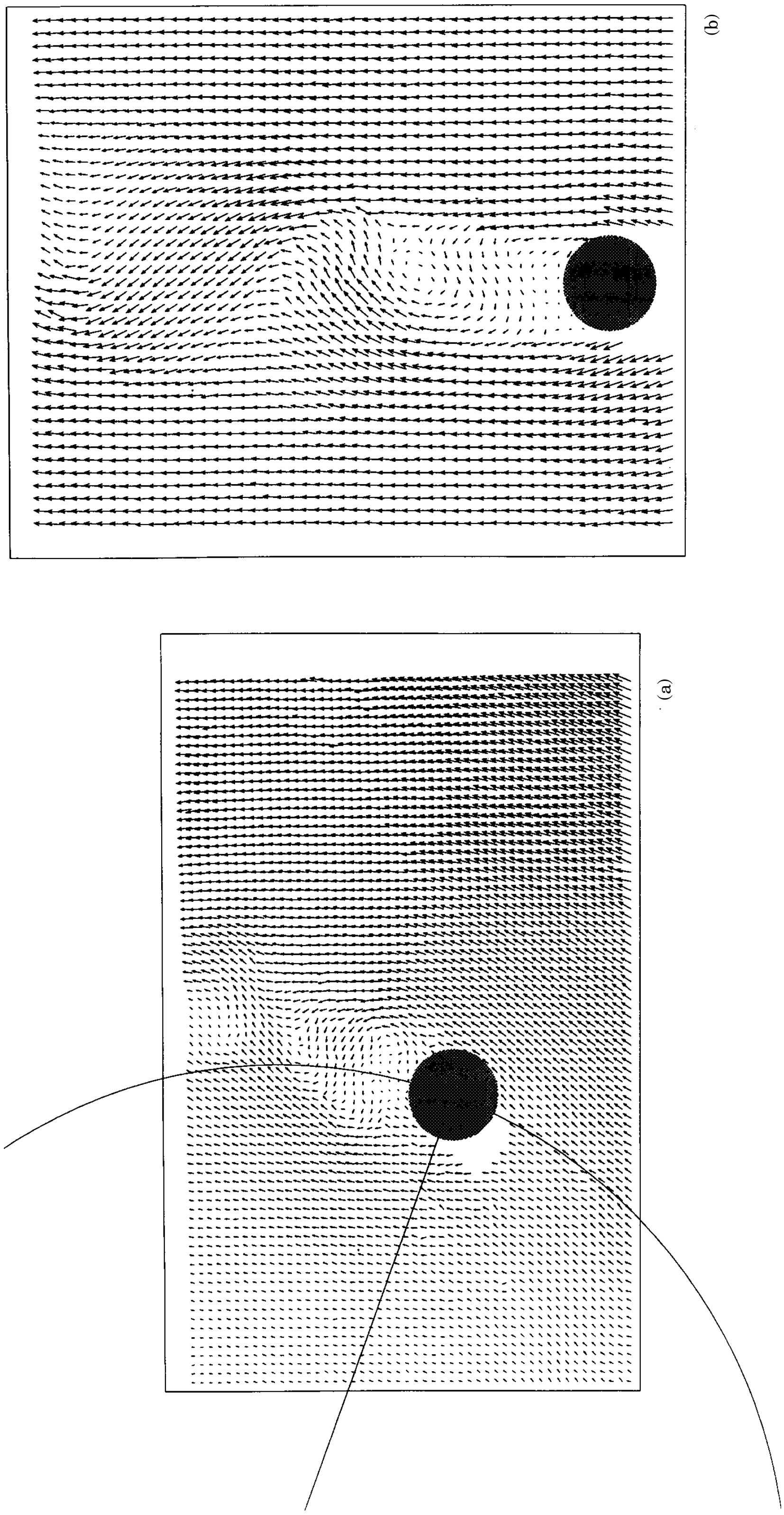

Figure 5. Typical velocity vector field measured using PIV: (a) the orbiting cylinder wake; (b) stationary cylinder wake (Wu *et al*. 1994).

Based on the Williamson *et al.* (1995) experimental correlation for the frequency of the shear layer vortices, it is proposed that the wavelength of the shear layer vortices is given by

$$\lambda/D = 34/\sqrt{\mathrm{Re}}$$

where Re is the Reynolds number. For $\mathrm{Re} = 1600$, $\lambda/D = 0{\cdot}85$, which is close to the shorter of the two wavelengths in Figure 4. Therefore, it can be hypothesized that the mechanism of switching to the broken-down pattern of Figure 3(b) is the development of the shear layer vortices, probably as a consequence of being perturbed by the upstream (or, identically, the far wake of the cylinder) velocity fluctuations. The development process of these shear layer vortices was so strong that the Kármán vortices were effectively suppressed and replaced with multiple small-scale vortices.

Previous work by Chyu & Rockwell (1996) has found that the formation length of the Kármán vortices contracts in response to external perturbation of the Kelvin-Helmholtz vortices. Similar observations were made by Prasad & Williamson (1997), where they found that stronger shear layer vortices appear to result in a reduced formation length of the Kármán vortices. Thus, the contraction of the wake is consistent with other studies; the mechanism whereby this occurs requires further study.

3.2. PIV Velocity Field Measurement in Near-Wake Region

PIV was used to quantify the vorticity field of the large-scale Kármán vortices in the near wake region. Figure 5(a) shows a typical velocity vector field in the rotating frame of reference. The circular arc in the figure indicates the orbiting path traced by the cylinder. For comparison, the velocity vector field of the vortex street of a stationary cylinder is presented in Figure 5(b), based on the experimental results of Wu *et al.* (1994).

In general, the formation of a vortex shed from the orbiting cylinder is similar to that of the stationary cylinder. However, the vortices in the near wake of the orbiting cylinder appear to be more developed and to form closer to the back of the cylinder.

The vortex formation length for both the orbiting cylinder and the stationary cylinder were obtained by measuring the distance between the cylinder centres and the centre of the rolled-up vortices immediately behind the cylinders. The results for vortex formation length L normalized by cylinder diameter D are listed in Table 1. Formation length data at $\mathrm{Re} = 1600$ extracted from a summary given by Unal & Rockwell (1988) are also included as a reference.

It is clear that there is a substantial shortening of the vortex formation length in the orbiting cylinder case. It is conjectured that the reduction in the vortex formation length is caused by a high freestream turbulence level, since the freestream flow is also the far wake of the orbiting cylinder.

Table 1
A comparison of cortex formation length: $\mathrm{Re} = 1600$.

	Orbiting cylinder	Stationary cylinder	Unal & Rockwell
L/D	$0{\cdot}80 \pm 0{\cdot}32$	$2{\cdot}4 \pm 0{\cdot}95$	$2{\cdot}3 \pm 0{\cdot}5$

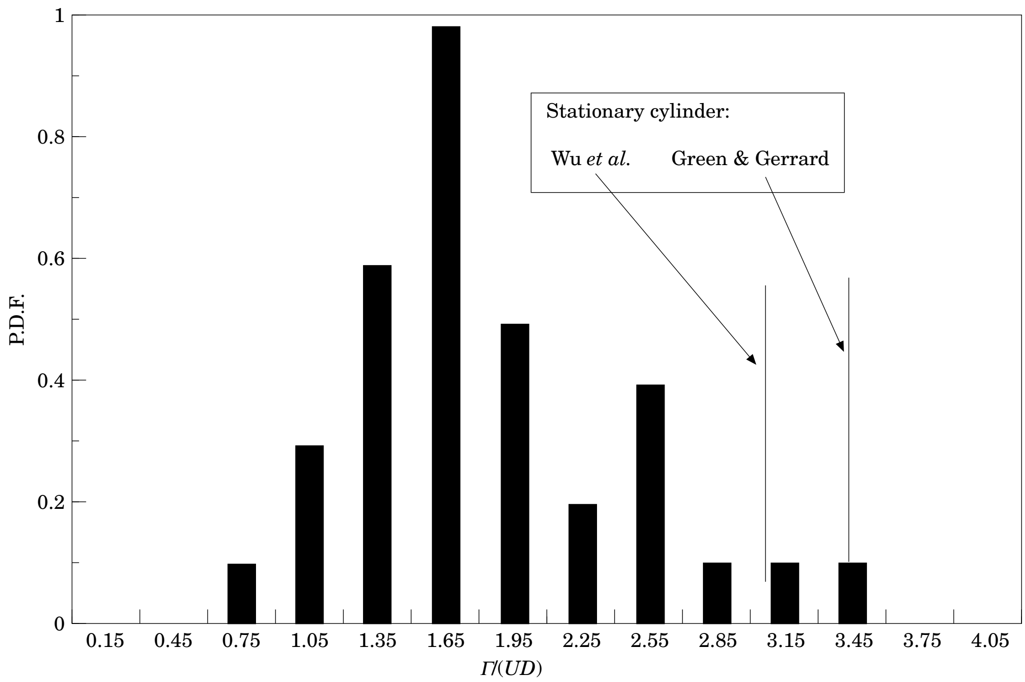

Figure 6. Near-wake vortex circulation P.D.F., Re = 1600. The circulation is normalized by U, the rotating velocity at the cylinder centre, and D, the cylinder diameter.

Figure 6 shows a P.D.F. of the absolute value of the normalized vortex circulation obtained from integrating vorticity over vortices in the near-wake region. Here the boundary of a vortex is defined as the contour at which the vorticity level becomes 10% of the maximum vorticity of the vortex. Included for comparison are results from a PIV measurement of the near wake flow field of a stationary cylinder by Wu *et al*. (1994) and the vorticity measurement by Green & Gerrard (1993) at a lower Reynolds number ($\mathrm{Re} \approx 200$).

Thus, the circulation of vortices in the wake of the orbiting cylinder is only about half that found in stationary cylinder wakes. The mechanism of this circulation reduction is not entirely clear. Probably it is due to enhanced cross-cancellation between opposite-signed vorticity in the near wake region, but it might also be due to reduced fluid entrainment into the rolled-up vortices, since there is a shortening of the vortex formation length. Further work is needed to clarify this phenomenon.

4. CONCLUSIONS

The wake behind a circular cylinder orbiting in a tank has been investigated experimentally using image de-rotation and PIV. It is shown that vortex structures in the near-wake region switch frequently from the classical Kármán vortices to multiple small-scale vortices. Based on the streamwise wavelength data presented, the small-scale vortices appear to be related to the Kelvin-Helmholtz vortices found in free shear layers. PIV measurements also show that there is a reduction in vortex formation length in the wake of the orbiting cylinder. A reduction in vortex circulation is also observed.

References

Bloor, M. S. 1964 The transition to turbulence in the wake of a circular cylinder. *Journal of Fluid Mechanics* **19,** 290–304.

Chaplin, J. R. 1988 Loading on a cylinder in uniform oscillatory flow: Part I–planar oscillatory flow. *Applied Ocean Research* **10,** 120–128.

Chyu, C. K. & Rockwell, D. 1996 Near-wake structure of an oscillating cylinder: effect of controlled shear layer vortices. *Journal of Fluid Mechanics* **322,** 21–49.

Coutanceau, M. & Defaye, J. R. 1991 Circular cylinder wake configurations: a flow visualization survey. *Applied Mechanics Reviews* **44,** 255–305.

Green, R. B. & Gerrard, J. H. 1993 Vorticity measurements in the near wake of a circular cylinder at low Reynolds numbers. *Journal of Fluid Mechanics* **246,** 675–691.

Kourta, A., Boisson, H. C., Chassaing, P. & Minh, H. Ha. 1987 Nonlinear interaction and the transition to turbulence in the wake of a circular cylinder. *Journal of Fluid Mechanics* **181,** 141–161.

Monkewitz, P. A. 1996 Personal communication.

Niemann, H.-J. & Holscher, N. 1990 A review of recent experiments on the flow past circular cylinders. *Journal of Wind Engineering and Industrial Aerodynamics* **33,** 197–209.

Prasad, A. & Williamson, C. H. K. 1997 The instability of the shear layer separating from a bluff body. *Journal of Fluid Mechanics* **333,** 375–402.

Rigby, G. D. & Evans, G. M. 1996 An investigation of gas jet break up in mixing processes. *Proceedings Chemeca 96*, Sydney Australia, Vol. 6, pp. 117–122.

Roshko, A. 1993 Perspectives on bluff body aerodynamics. *Journal of Wind Engineering and Industriual Aerodynamics* **47,** 79.

Sheridan, J., Soria, J., Wu, J. & Welsh, M. C. 1992 The Kelvin-Helmholtz instability of the separated shear layer from a circular cylinder. In IUTAM Symposium Proceedings, *Bluff-Body Wakes, Dynamics and Instabilities*, pp. 115–118.

Unal, M. F. & Rockwell, D. 1988 On vortex formation from a cylinder. Part 1. The initial instability. *Journal of Fluid Mechanics* **190,** 491–512.

Wei, T. & Smith, C. R. 1986 Secondary vortices in the wake of circular cylinders. *Journal of Fluid Mechanics* **169,** 513–533.

Williamson, C. H. K. 1985 Sinusoidal flow relative to circular cylinders. *Journal of Fluid Mechanics* **155,** 141–174.

Williamson, C. H. K 1988 The existence of two stages in the transition to three-dimensionality of a cylinder wake. *Physics of Fluids* **31,** 3165–3168.

Williamson, C. H. K. 1996 Vortex dynamics in the cylinder wake. *Annual Review of Fluid Mechanics* **28,** 477–539.

Williamson, C. H. K., Wu, J. & Sheridan, J. 1995 Vortex scales in the wake of a cylinder. *Physics of Fluids,* **7,** 2099–2101.

Wu, J., Sheridan, J., Soria, J. & Welsh, M. C. 1994 An investigation of unsteady flow behind a circular cylinder using a digital PIV method. In *Laser Anemometry 1994–Advances and Applications*, FED-Vol. **191,** 167–172. New York: ASME.

Wu, J., Sheridan, J., Hourigan, K., Soria, J. 1996a Shear layer vortices and longitudinal vortices in the near wake of a circular cylinder. *International Journal of Experimental Thermal and Fluid Science*, **12,** 169–174.

Wu, J., Sheridan, J., Welsh, M. C. & Hourigan, K. 1996b Three-dimensional vortex structures in the wake of a cylinder. *Journal of Fluid Mechanics* **312,** 201–222.

Wu, J., Pullum, L., Yunken, R. & Welsh, M. C. 1996c Rapid diagnosis of flow separation around an impeller in a mixing vessel. *Experiments in Fluids* (in press).

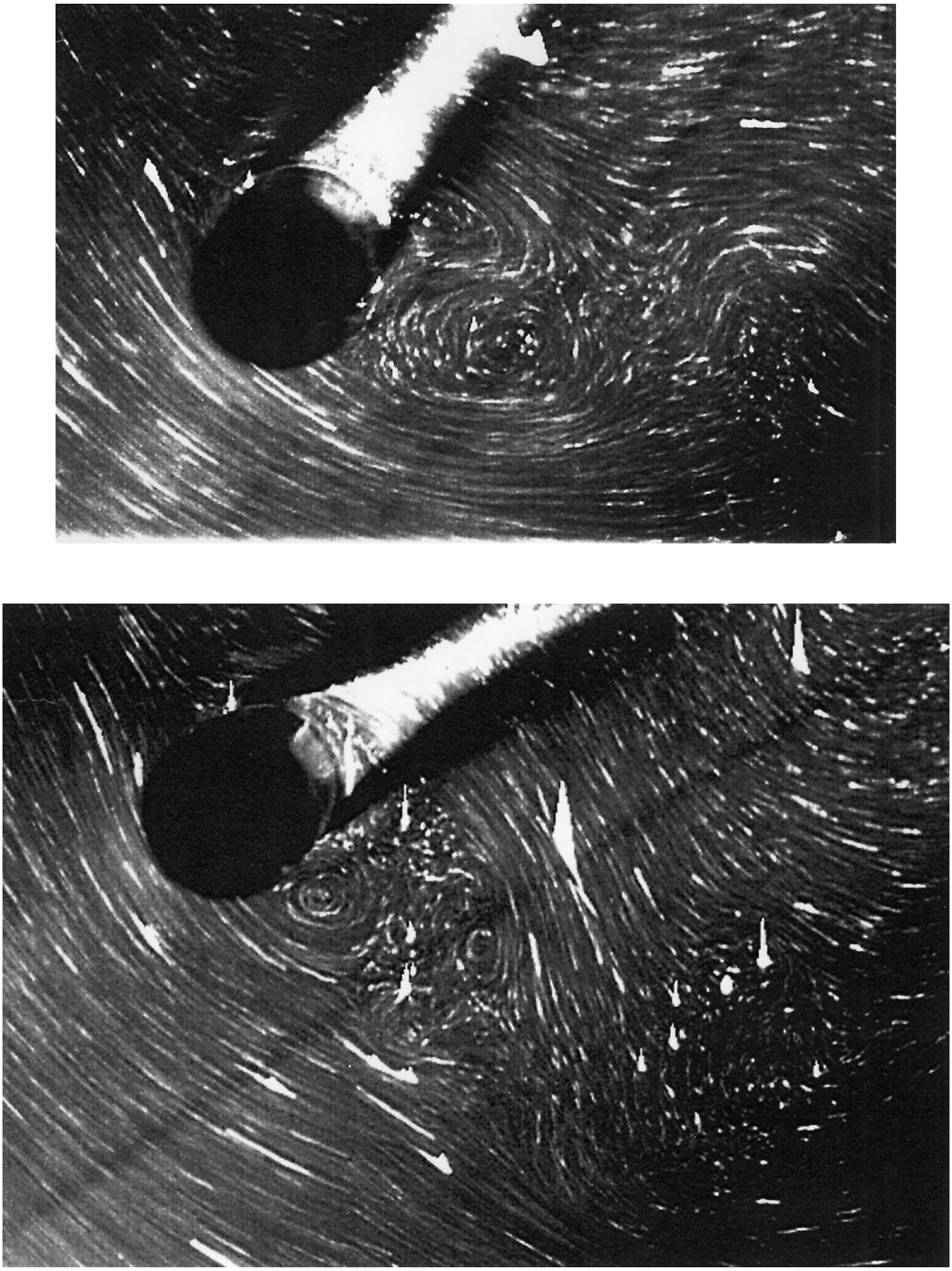

Figure 3. Wake development recorded in the rotating frame of reference. (a) Kármán vortices, (b) multiple small-scale vortices.