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THREE-DIMENSIONAL VORTEX STRUCTURES IN BLUFF-BODY WAKES

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ABSTRACT
The primary objective of this study was the characterization of the three-dimensional longitudinal vortices found in the wake of a circular cylinder. Using Particle Image Velocimetry (PIV) full instantaneous velocity fields were obtained in the transverse plane containing the cylinder. Footprints of the longitudinal vortices were identified, showing up as counter-rotating vortex pairs. It appears that these vortices are embedded between, and locked to, the Kármán vortices. From measured peak vorticity fields, it is clear that the longitudinal vortices are being stretched by the Kármán vortices.

NOTATION

D	Diameter of cylinder (m)
Re	Reynolds number based on cylinder diameter
U_0	Freestream velocity (m/s)
u	Streamwise component of velocity (m/s)
w	Spanwise coordinate of velocity (m/s)
x	Streamwise coordinate (m)
y	Transverse coordinate (m)
z	Spanwise coordinate (m)
ω_y	Vorticity component in y-direction (s^{-1})
ξ_y	Normalised y-component of vorticity.
ξ_z	Normalised z-component of vorticity.

INTRODUCTION
Roshko (1954) in an early study of cylinder wakes noted discontinuities in the Strouhal number versus Reynolds number relationship which he speculated might be the result of the first appearance of three-dimensional effects in the wake.

Later, Hama (1957) noted the presence of three-dimensional effects in the wake, based on flow visualisations. At Reynolds numbers above 150 he found a transverse waviness, consistent with vorticity in the transverse and/or the streamwise directions. Based on hot-wire results, Grant (1958) found that above certain Reynolds numbers the Kármán vortices developed three-dimensionalities, manifested as counter-rotating streamwise vortices.

Gerrard (1978), again using flow visualisation, observed "knots" of dye forming along the span of the cylinder at Reynolds numbers above 140. He proposed that these were indicative of three-dimensionality in the wake.

It seems likely that all of these early studies were finding the same phenomenon, the presence of longitudinal vortices in the wake. These vortices are inclined at an angle to the streamwise direction, thus having components of vorticity in the streamwise (x-direction) and transverse directions (y-direction, Fig. 2).

More direct evidence of the three-dimensional structure of the wake has been presented in the more recent work of Williamson (1988), Wei and Smith (1986), Welsh et al. (1992), Bays-Muchmore and Ahmed (1993) and Wu et al. (1994a, b). Wu et al. (1994b) have measured the instantaneous velocity field using PIV and from this derived the vorticity field. Mansy et al. (1994) used a scanning laser anemometer and so were also able to measure the velocity field. Both Mansy et al. and Wu et al. (1994a) measured the effect of Reynolds number on the spanwise wavelength of the structures.

Similar structures have been found in mixing layers by Bernal and Roshko (1986). In both cases the longitudinal vortices leave a "footprint" of mushroom-type structures in the near-wake.

Measurements taken at higher Reynolds numbers by Hayakawa and Hussain (1989) have also shown the presence of inclined, longitudinal vortices in the wake. Their measurements were made using an X-wire rake further downstream than those discussed above. From the form of "footprint" found they proposed that the three-dimensionality could be described as ribs wrapping around rolls (Kármán vortices) or ribs in the braid.

Results are presented here in which the instantaneous velocity field was measured in the transverse plane (xz-plane, Fig. 2) of the near wake. All measurements were made using a specifically-developed PIV system which allowed for the capture of all the velocity data on the specified plane. Consequently, the vorticity, circulation, geometry and topology of the longitudinal vortices could be extracted; results are presented below.

EXPERIMENTAL FACILITIES

The measurements were all made in the CSIRO water tunnel at Highett. The tunnel, shown in Fig.1, has a 770mm long 244 x 244 mm working section, constructed from acrylic, in which the free-stream velocity was uniform to within 1% outside the wall boundary layers. The spectrum of the fluctuating longitudinal velocity was free of sharp peaks and decreased in amplitude by 20dB/Hz above 0.08Hz. Typically, the longitudinal turbulence was less than 0.15%. All cylinders used were made from plexiglass, were 244 mm long, and either 6.4 or 9.4 mm in diameter.

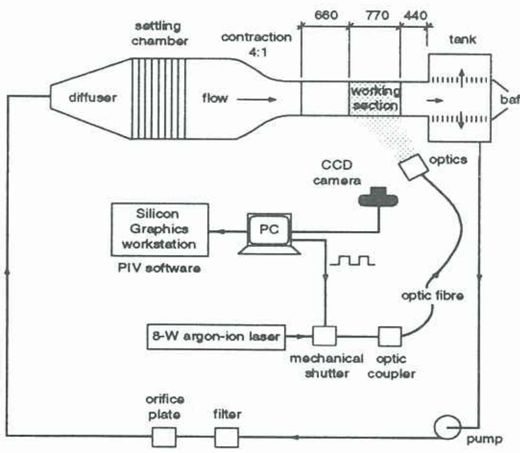

Figure 1. Return circuit water tunnel and PIV image system.

Adrian (1991) has provided an excellent review of the PIV method in general and only a brief description of the method used follows; a more complete description is available in Wu et al. (1994d). Hollow Q-Cel microspheres were used to seed the flow. These had a mean diameter less than 30μm. A 6W Argon-Ion laser provided the light, which was formed into a sheet by a cylindrical lens. The light sheet was pulsed using a mechanical shutter. A "Videk" digital CCD camera recorded the light scattered by the particles. The camera has a spatial resolution of 1280 x 1024 pixels and the light was digitised into 256 grey-levels on a personal computer. The data was transferred to a Silicon Graphics workstation, where the bulk of the processing was done. Raw images were converted into velocity fields using purpose-built software based on the digital Young's fringe method.

RESULTS

Reynolds number, based on cylinder diameter and free-stream velocity, was the main independent variable; this dependence being one of the reasons for studying the cylinder wake. Data will be presented for a Reynolds number of 525, this being part of a larger set in the range $140 \leq Re \leq 550$. The value chosen for fuller consideration is well beyond the transition Reynolds number at which the vortices are first observed (Williamson 1988, Wu et al. 1994a), meaning the longitudinal vortices are fully-developed and represent the form found over a wide range of Reynolds numbers. The two components of velocity field in the plane of the laser sheet were measured, thus allowing the calculation of the vorticity component normal to the laser sheet.

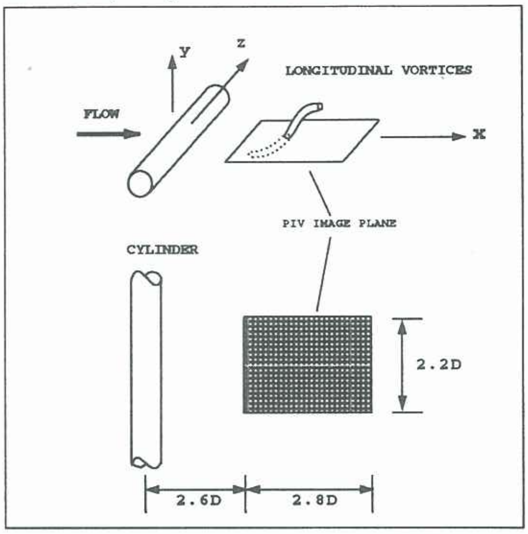

Fig.2 . PIV image plane and coordinate system used in measuring the velocity field of the longitudinal vortices.

All data presented were taken on the centreline transverse plane (y=0) two diameters downstream of the cylinder, see Fig.2. To obtain accurate estimates of the vorticity of what are basically fine-scale structures, it was necessary to focus attention on a small area for investigation. Thus, measurements were made over an area of 26 x 21 mm (cylinder diameter of 9.4 mm) which gave a velocity vectors on a grid of 0.5 mm.

Figure 3(a) shows a sample velocity fields at a Reynolds number of 525. The case presented was acquired randomly with respect to the phase of the Kármán shedding cycle. When the convection velocity of the Kármán vortices is removed, i.e. the flow is mapped into the moving frame of reference, Figure 3(b) results; here the longitudinal vortices are clearly evident.

Perry and Steiner (1987) used the concept of "sectional streamlines" to represent the instantaneous flow in a plane cutting the three-dimensional field. Such streamlines are useful in examining the topology of the flow in terms of critical points, as first suggested by Perry and Fairlie (1974). This approach was found useful in this study, the streamlines being obtained by integrating the velocity field out from an initial value using a predictor-corrector scheme. Bi-linear interpolation of the measured velocity field was used .

Fig. 3(c) shows the instantaneous sectional streamlines calculated from the velocity field in the moving frame of reference i.e. Fig. 3(b). The footprint of the longitudinal vortices is again clearly evident. Pairs of vortices are located along the span of the cylinder. These result from the laser sheet cutting the inclined vortices in the measurement plane. Wu et al. (1994a) have shown these are located in the braid region between consecutive Kármán vortices. Figure 4 shows results from two arbitrary instants. To characterise the topological structure of the flow near the foci formed by the longitudinal vortices, 50 frames of velocity distributions were classified into the three categories of foci in the measurement plane. The results are shown in Fig. 5. A vortex is considered to be undergoing stretching normal to the measurement plane if the sectional streamlines spiral in towards the foci, to be undergoing compression if they spiral away from the foci, and to be neutral if they form limit cycles around the foci.

From 50 frames of instantaneous velocity data at a Reynolds number of 525, 130 vortex pairs were examined. Of these 83% were found to have streamlines spiraling in towards the focus, 13% spiraling out, and 4% approaching a limit cycle. This leads one to conclude that the cores of most of the longitudinal vortices intersecting the centreline transverse plane (y=0) are being stretched normal to the plane of measurement.

The vorticity component normal to the plane of measurement, defined as $\omega_y=\partial w/\partial x - \partial u/\partial z$, can also be found from the discrete velocity data. Figure 6 shows the probability density functions for the vorticity distribution at the centre of the vortices. The freestream velocity and cylinder diameter are used to normalise the transverse vorticity component, ω_y, as $\xi_y = \omega_y/(U_oD)$. It can be concluded from Fig. 6 that the means of both positive and negative vorticity are approximately equal to $\xi_y=\pm7.3$. Measured PIV results show that the maximum spanwise vorticity of a shed Kármán vortex is approximately ξ_z=4-5 at Re=525. Therefore the maximum vorticity of the longitudinal vortices is greater than that of the spanwise vortices in which they are embedded.

This result is consistent with the notion that most of the vortices are being stretched normal to the measurement plane as concluded earlier in the present paper. If the longitudinal vortices are hypothesised to originate from the distortion of spanwise vortices, then a higher vorticity of the longitudinal vortices is consistent with the vortex stretching theory.

CONCLUSIONS

Results have been presented which characterise the longitudinal vortices found between the Kármán vortices in the wake of circular cylinders at low Reynolds numbers. In particular, they have been shown to have levels of vorticity which can be higher than that of the Kármán vortices. The high levels of vorticity are consistent with a vortex dynamics model which show that the longitudinal vortices emanate from a distortion of the vorticity in the separating shear layers.

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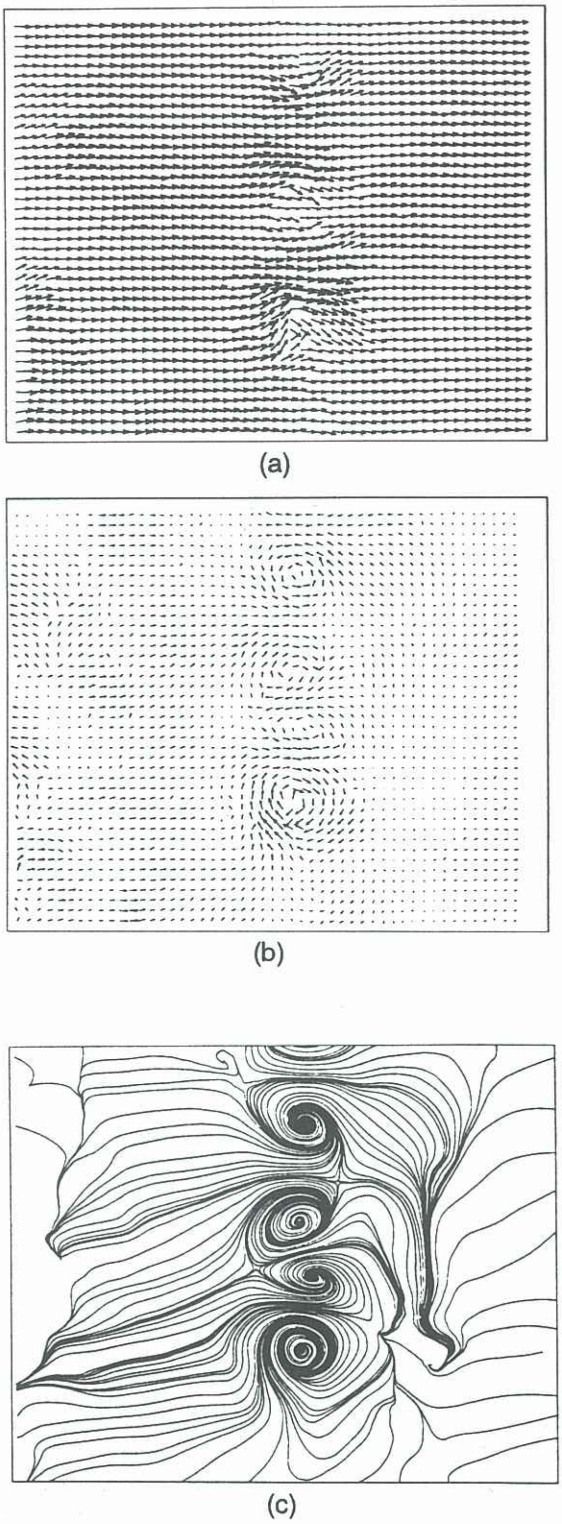

Figure 3 Velocity field in the transverse plane (x-z plane) for typical velocity fields: (a) seen in a stationary frame of reference; (b) seen in a frame of reference moving at 60% of U_0 ; (c) sectional streamlines in the moving frame of reference.

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Figure 4. Instantaneous sectional streamlines: two samples at arbitrary instants, the frame of reference is moving with the vortices.

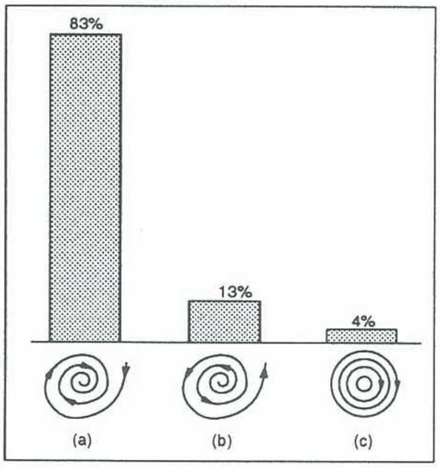

Figure 5. Survey of the topology of the focus based on instantaneous sectional streamlines around a focus: (a) spiralling out, unstable focus;(b) spiralling in, stable focus; (c) limit cycle.

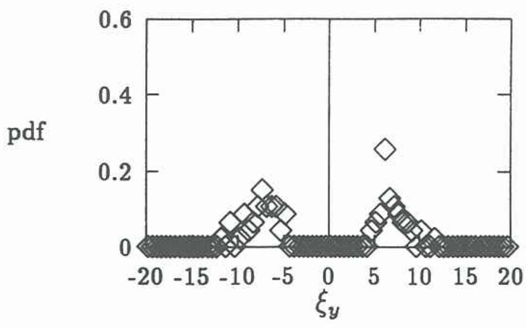

Figure 6. Vorticity component fluctuations at the centres of the longitudinal vortices.

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