ABSTRACT

A survey is conducted to quantitatively visualise the wake flow behind a circular cylinder at Reynolds numbers of 180 to 2500. A time-resolved tomographic PIV method is used to measure the sequence of three-dimensional vector fields evolving in time. The attention is focused upon the unsteady 3D wake organization with the interaction of primary rollers (Karman-Benard) and the secondary vortices resulting from 3D instability of the vortex wake.

A cylinder of 12 mm diameter is immersed in a water channel of 600×600 mm$^2$ test section of which only the upper half channel is used. A volume of 80×50×16 mm$^3$ is illuminated by a 2×200 mJ laser and recorded by 4 cameras with 2k×2k pixels viewing the volume from different directions distributed over a solid angle of 45 degrees. The images are processed by a modified MART tomographic reconstruction algorithm to first reconstruct the intensities of all voxels in the illuminated volume. The volume reconstruction is followed by a three-dimensional cross-correlation between interrogation volumes returning approximately 300,000 vectors at every snapshot. At low free-stream velocity, the recording system is operated in continuous-mode achieving a recording rate of 20 Hz, which provides time-sequences with higher temporal resolution. However, at velocities exceeding 5 cm/s only acquisition in double-frame mode can ensure the appropriate time separation for cross-correlation. Nevertheless, the time resolution is sufficient for the description of dynamic events up to a flow speed of 15 cm/s.

To the authors’ knowledge, this type of measurement is unprecedented: for the first time it has been possible to measure small-scale 3D-flow features in a complete volume time-resolved with high spatial resolution. Sample results are presented showing the evolution of spanwise vortices and pairs of counter-rotating secondary interconnecting structures, characterized by different spacing as a function of the Reynolds number. The high-computational load for data processing keeps the investigation still in progress at present time.

1 INTRODUCTION

The transition from the two-dimensional vortex shedding regime behind circular cylinders to three-dimensional flow governed by the Reynolds number has been investigated extensively, especially at
Reynolds numbers in the order of $10^2 - 10^3$. More background about these studies can be found in the work by e.g. Williamson et al. [1, 2, 3]. The Reynolds number is defined here as $Re = V_{\infty}D/\nu$, with $V_{\infty}$ denoting the free-stream velocity, $D$ the cylinder diameter and $\nu$ the kinematic viscosity of the fluid. For relatively low Reynolds numbers ($Re = 50-190$), the dominating features of the wake are the well-known alternating rollers, i.e. a von Kármán vortex street (Williamson, [3]). The wake is quasi-two-dimensional in this regime. The earliest 3D transition is associated with the inception of vortex loops in the main rollers around $Re = 190$, which distort the primary rollers with a spanwise wavelength $\lambda_z$ between 3 and 4 diameters (Mode A, Williamson and Roshko [1]).

Increasing the Reynolds number to about 250, a transition from Mode A (vortex loops) to Mode B (stream-wise vortex pairs, Williamson [2,3]) can be observed. These two modes have been identified as the two dominant modes for the three-dimensional organisation of coherent structures in the 3D cylinder wake regime. In particular Mode B is characterised by a shorter span wise wavelength ($\lambda_z/D = 1$ between counter-rotating stream-wise rollers). The application of PIV allowed a quantitative analysis of these secondary vortices. Brede et al. [4] obtained $\lambda_z/D = 4.5$ for Mode A and confirmed $\lambda_z/D = 1.0$ for Mode B. At Reynolds numbers exceeding $10^3$ the interaction between the streamwise and the Kármán rollers has been investigated by Bays-Muchmore and Ahmed [5], who used planar laser fluorescence to visualise mushroom-shaped structures interconnecting the spanwise rollers.

A recent PIV survey along orthogonal planes performed in the range $Re = 2,000-10,000$ by Huang et al. [6] showed a more chaotic wake structure, which was attributed to the transition occurring within the separated shear layers. The full three-dimensional wake structure can nowadays be simulated with DNS, as performed by Thompson et al.[7]. However, experimental data is lacking for a comparison of the full three-dimensional wake structure and even the latest planar velocimetry surveys do not render the instantaneous 3D organisation of the wake. From the above experimental studies, a number of issues are not yet elucidated. In particular at higher Reynolds numbers, the secondary vortices model is based on planar cross-sections and the instantaneous three-dimensional organisation of the flow field has therefore not been sufficiently understood.

Moreover, the quantitative characterisation of the secondary vortices dynamics requires an evaluation of the stretching term in the Navier-Stokes equations in vorticity form. This term has not been investigated experimentally due to the technical limitation of the planar PIV technique. The present study approaches the analysis of the instantaneous three-dimensional organisation of the coherent flow structures present in the vortex wake applying the recently developed 3D velocimetry technique Tomographic PIV (Tomo-PIV, Elsinga et al. [8,9]).

Previous work done in air at $Re = 2700$ (Scarano et al. [10]) has shown the potential of Tomo-PIV for characterising quantitatively the three-component velocity vector field over a volume containing the cylinder wake. The current work uses larger format CCDs and further extents the analysis to a range of Re-numbers from 180 to 2500. By recording time-resolved velocity fields it also provides insights in the temporal evolution and interaction of flow features.

## 2 EXPERIMENTAL SET-UP

### 2.1 Flow facility and model

The experiments are performed in a water channel with a 60×60 cm$^2$ cross-section and a test section with 5 meters length. The channel is split in two parts by a flat plate installed for boundary layer
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studies. The upper part of the channel is used in the present experiment with an open water surface. The free-stream turbulence level is approximately 1% due to flow conditioning in the plenum and a 6:1 area contraction upstream of the test section. The mean flow speed can be chosen in the range between 1 cm/s and 1 m/s. A 12-mm diameter Perspex cylinder is placed 50 cm downstream of the entrance of the test section and in the middle of the channel at 15 cm from the bottom (Fig. 1 and 2).

2.2 Diagnostics apparatus

Hollow glass spheres of 30 μm diameter are used as tracer particles (3M glass bubbles S60, r.d. 0.6). The estimated response time is in the order of 10 microseconds. They are therefore expected to follow the fluid motion accurately in the current study where the characteristic time scale ranges between 50 and 500 milliseconds. Achieving and maintaining the required seeding level in the facility is crucial for the Tomo-PIV technique. In the present experiment a seeding concentration of approximately 1 particle/mm³ is aimed at by introducing 50 grams of tracer material in approximately 10 m³ of water.

The tracer particles are illuminated by a double-pulse Nd:YAG laser (Quantel CFR, 200 mJ/pulse) running at maximum power. The laser beam is expanded using a beam expander and a cylindrical negative lens to generate a nearly collimated beam covering the measurement volume. A sharp light cut-off at the edges of the illuminated volume is obtained by knife-edge slits placed in the beam path before it enters the water channel. The beam is aligned with the cylinder orientation and illuminates a measurement volume approximately 10 cm wide and 1.6 cm thick.

Four cameras (Imager Pro X, 2048×2048 px, 14-bit) are installed above the channel, viewing the cylinder wake to record a field-of-view of approximately 6(L)×4(W)×1.3(H) diameters directly behind the cylinder, see Fig. 1. A Plexiglas plate is placed at the water level to obtain a stable optical interface for the optical path of the cameras. The cameras are equipped with 60-mm Micro Nikkor

Fig. 1. Orientation of measurement volume relative to cylinder shown with H₂-bubble visualization. D = 12 mm. The recorded volume starts 5 mm behind the cylinder.
lenses (mounted on Scheimpflug adapters). Cameras and laser are controlled with a programmable timing unit (PTU) and DaVis 7 (LaVision GmbH).

The cameras are placed at angles of approximately 20 degrees with respect to the vertical (Fig 2). Two cameras are recording light in “backscatter” mode whereas the other two are receiving light in “forward” scatter mode. The slight difference in the observed scattering intensity is compensated by using different apertures: $f_{\text{back}} = 16$ for the backscatter cameras, $f_{\text{forward}} = 22$ for the forward cameras. In both cases the aperture results in a depth-of-field that allows to image all the illuminated particles in focus. Optical distortion of the tracer images due to non-orthogonal medium changes (air/Perspex/water) were not observed during the present experiment, which can be explained by the relatively small angle between the line of sight and the normal to the interface.

![Fig. 2: Schematic illustration of the set-up in side view (left) and photograph taken in top view (right) showing the camera placement. The cylinder (parallel with the vertical aluminum beam) is marked with a ‘c’ (the lines indicate the size). The volume-illuminating beam enters from the top of the image (i.e. from the side of the facility), parallel to the cylinder.](image)

The 3D calibration of the imaging system is done recording the image of a calibration plate at several positions in the volume. The calibration plate is mounted on a computer-controlled translation stage with micrometer precision. After calibration, the plate is removed from the facility. The calibration is repeated after each measurement series to verify that the camera alignment has not changed. Additional recordings have been taken by illuminating the volume only within a thin slice at the front and back of the full volume. These images are used to verify the orientation of the calibration plate with respect to the volume by means of a self-calibration technique (Scarano et al. [11], Wieneke [12]). Additionally, the exact locations of the front and back planes of the volume are verified and the volume mapping function is tilted to align the xy-plane of the world coordinate system with these planes.
2.3 Experiment campaign

The flow facility and the measurement system allowed time resolved experiments within the range of $Re = 180-2520$, which was obtained changing the free-stream flow velocity in the range of $V_\infty = 0.015-0.21$ m/s. Table 1 contains the details of the experimental conditions. In all experiments the cameras are used in double-frame mode except for the lowest flow velocity where a single-frame continuous recording is also attempted. The interpulse time $d_{\text{laser}}$ is varied in order to maintain the reference particle displacement constantly equal to 0.5 mm (approximately 10 voxels). The time elapsing between subsequent velocity measurements $d_{\text{vector}}$ depends essentially on the acquisition rate of the imaging system, which in the present case varied between 7 and 10 Hz. Only for the case at lowest velocity with the continuous acquisition mode the effective acquisition frequency is approximately doubled to 20 Hz. The tomographic system is operated at a digital resolution of 24 voxels/mm.

<table>
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<th>Reynolds number</th>
<th>$V_\infty$ [m/s]</th>
<th>$d_{\text{laser}}$ [ms]</th>
<th>$d_{\text{vector}}$ [ms]</th>
<th>reconstructed volume [mm]</th>
<th>[voxel]</th>
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<td>180</td>
<td>0.015</td>
<td>50.9</td>
<td>50.9</td>
<td>$73 \times 46 \times 16$</td>
<td>1730 $\times 1089 \times 377$</td>
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<td>180</td>
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<td>33.0</td>
<td>101.8</td>
<td>$73 \times 46 \times 16$</td>
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<tr>
<td>360</td>
<td>0.030</td>
<td>17.0</td>
<td>101.8</td>
<td>$73 \times 46 \times 16$</td>
<td>1730 $\times 1089 \times 377$</td>
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<tr>
<td>360</td>
<td>0.030</td>
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Table 1. Recording parameter. The volume is specified in streamwise $\times$ spanwise $\times$ height dimension. The scaling factor is 0.0424 mm/voxel.

3 DATA PROCESSING

The tomographic reconstruction technique based on the MART method (Herman and Lent [15]) requires a low background noise level in the recordings. This is achieved by digital processing of the images, which allows to remove background and decrease the random noise present in the images.

Fig. 3. Comparison of original (left) and preprocessed image (right). Area show is 140×100 pixel.
recordings. First, the local background intensity is removed by subtracting the minimum gray value of each pixel computed over all images in time. This effectively removes any constant background. A local intensity normalization equalizes particle intensity differences between cameras and between different parts of each image. These differences can arise from the viewing direction (e.g. forward versus backward scattering) and other effects. This step is done to correct for large-scale differences in intensity. A min-max filter (Westerweel [14]) enhances weak particles and improves the signal-to-noise ratio for the cross-correlation step. Finally, a 3×3 Gaussian filter removes any residual image noise, which stabilizes the tomographic reconstruction process. A similar processing has been proposed by Elsinga et. al. [9]. Fig. 3 shows a comparison between original and preprocessed image.

Tomographic reconstruction of the intensities of all voxel in the recorded volume is done by an iterative MART algorithm, which is discussed with more details in Elsinga et. al. [8]. In its essence the process iteratively attempts to find a distribution of voxel intensities which, back-projected on the 4 cameras, gives the best agreement with the recorded images. The seeding density should be in the range of 0.03 to 0.1 particles-per-pixel in the images for optimal results. A higher seeding density has been proven to lead to an increased percentage of spurious light intensity reconstructed within the volume. Such spurious light is also commonly referred to as “ghost” intensity or ghost particles in 3D-PTV applications. Conversely, when the seeding concentration is too low, the spatial resolution of the system is reduced due to the lower spatial sampling rate of the velocity field by the particle tracers.

Once the volume is reconstructed for the two subsequent exposures, a 3D-cross-correlation between interrogation volumes computes the 3D-vector field. Advanced iterative methods with deformed interrogation windows have been implemented extending successful techniques known from 2D-PIV to 3D (Scarano et.al. [13]).

Fig. 4. Left: Re=540. Iso-surfaces of the vorticity vector magnitude. The iso-surfaces are color-coded according to the dominant component: when $\omega_z$ is dominant the color is cyan ($\omega_z < 0$) or green ($\omega_z > 0$); when $(\omega_x^2 + \omega_y^2)^{0.5}$ is dominant blue or red depending on the sign of $\omega_x$. Right: for comparison result from DNS computation at Re=250 (Mode B shedding, Thompson et al. [7]).
Fig. 5. Instantaneous vector fields for $Re = 360$ to 1260. Same coloring as in Fig. 4. The iso-contour value is increasing for larger Re-numbers from 6 to 30 s$^{-1}$. At Re=1080 a series of spanwise aligned vertical vortices is indicated by arrows.
The data has been processed with DaVis 7 using a final interrogation window size of 48×48×48 voxels (2×2×2 mm³, approximately 10 particles inside the interrogation box) with a 75% overlap leading to 141×89×29 = 360k vectors. The vector spacing is approximately 0.5 mm. Final, the vector field has been validated by a normalized median test (Westerweel and Scarano [16]). The total processing time for one volume vector field is about 4 hours on a PC with 4 dual-core CPUs.

4 RESULTS

Above about Re=190 the the onset of three-dimensional instabilities in the vortex wake becomes more evident and different type of secondary vortices is observed. The snapshot at Re=540 returns a series of counter-rotating streamwise vortices finger-shaped, which interconnect counter-rotating primary rollers. (Mode B, Williamson et al. [2,3]). The vorticity iso-surfaces show that the structures are spanwise organized following a periodic pattern (color blue/red in Fig. 4) at X/D = 2 with a spacing close to 1 D in agreement with existing experimental observations, however in less agreement with DNS computations returning a smaller spacing at even lower Re (Thompson et al. [7]), see Fig. 4 right. The experimental data at higher Re-number increases the range of flow scales as expected, which however makes the direct inspection of the wake structure somewhat less intuitive by visualization. The flow pattern measured for different Re-numbers is compared in Fig. 5. As a general trend, the spanwise coherence tends to be recovered at higher Reynolds, where the effect of the secondary structures becomes less pronounced and their length scale is reduced. In the snapshot at Re=1080 a series periodic structures aligned approximately in the vertical direction is captured at X/D = 3. The vertical position for the axis of the fingers corresponds approximately to their mid point where an inflexion is supposedly taking place. The further evolution of these structures on the

Fig. 6. Cut through xz-plane at y close to mid-plane with vorticity ω_y for Re=540 (left) and Re=1080 (right). The spacing between streamwise fingers is 0.75 D and 0.5 D, respectively.
upper part of the main roller is not in view in the present experiment due to the edge of the reconstructed domain. One entire shedding period downstream, at X/D = 7, a similar organization is repeated again, indicating a correlation between spanwise aligned events also in the streamwise direction. Fig. 6 shows a comparison of the vorticity field between Re=540 and Re=1080. A plane in the middle of the observation volume is selected and the vertical vorticity component $\omega_y$ is displayed. The cross-section of the finger-like structures is approximately circular and their spacing along the spanwise coordinate is inferred as approximately 0.5 D and 0.75 D for Re=1080 and 540, respectively.

Generally the 3D vortex break-down mechanism occurs more frequently for larger Re-numbers. Moreover oblique vortex shedding has also been observed to take place a number of times, which is ascribed to the limited control over the boundary conditions at side walls.

A time evolution of the full 3D flow pattern is shown in Fig. 7 for Re = 540. The intensity of the secondary flow structures equals or surpasses that of the main rollers, in terms of the local vorticity distribution. Although the vorticity pattern of the karman wake seems to vanish downstream of 5 diameters, the streamwise rollers show a significant persistence even up to the limit of the observed domain (X/D=7). [3]. Interestingly, a wider range of flow scales is observed very close to the cylinder within X/D<2, which then tends to decrease downstream. This can be explained either accepting a higher measurement noise close to the cylinder or speculating upon the effect of viscosity on the flow re-laminarization process. This aspect will be given attention in a further analysis of the experiments. Moreover, not the complete roller is covered by the recorded volume and further experiments should be conducted with smaller and larger cylinders to be able to look at the evolution of larger as well as smaller scale structures in more detail.

5 SUMMARY

Tomographic PIV has been employed as a high-resolution full-volume digital technique to quantitatively measure the wake flow behind a circular cylinder in water at Re = 180 to 2500. The measurement volume was 6(L)×4(W)×1.3(H) cylinder diameters directly behind the cylinder. Each instantaneous flow field contains 360k vectors with a spatial resolution of 0.5 mm. The repetition rate of the 4 cameras with 2k × 2k pixel was high enough for time-resolved measurements to analyze the development and flow structure interaction of secondary 3D-instabilities. For the first time it has been possible to measure small-scale 3D-flow features in a complete volume time-resolved with high spatial resolution. Many flow features described before in the literature have been identified in the preliminary analysis of the data. Further processing is necessary to fully exploit the information contained in the tomograms.

ACKNOWLEDGEMENTS

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Fig. 7. Time series at Re = 540. Coloring is the same as in Fig. 5.
REFERENCES