Large-scale tomo-PIV for on-site drag analysis in speed sports

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Abstract Large-scale tomographic Particle Image Velocimetry is proposed as a tool for the on-site aerodynamic investigation in speed sports. The ring-of-fire concept is presented, which relies upon a tomographic PIV system used during the training of athletes in speed sports. The system consists of a short tunnel installed in a velodrome, through which the athletes pass during their training. Helium-filled soap bubbles are used as flow tracers and images are recorded via high-speed digital cameras. The ring-of-fire concept allows measuring the airflow around athletes, and is suitable for aerodynamic investigation and drag minimization. The present study proves the feasibility of the concept by showing its working principle on small scale on the flow over a sphere.

1 Introduction

Aerodynamics plays a crucial role in many speed sports, where races are often won by fractions of a second. The aerodynamic drag acting on the athletes and their vehicle is often the main force the athletes have to overcome. In speed skating the aerodynamic drag can reach 80% of the total resistance, in road cycling over 90% [1]. A small reduction of the aerodynamic drag can mark the difference between winning and losing a competition.

To date, sport aerodynamics investigation has been conducted mainly via wind tunnel balance measurements and computational fluid dynamics (CFD) simulations. The effect of posture of bicycle riders, helmet shape, wheel and frame design on bicycle aerodynamics has been investigated by several authors [1, 2]. For speed skating, helmet and skin suit aerodynamics have been object of research [3]. Defraeye [4] used CFD modelling (RANS and LES) to estimate the aerodynamic drag and to evaluate the flow field around a cyclist on his bike in different positions.

Most studies focus on the measurement of the resulting drag force acting on the athlete or the sports equipment. Conversely, only a few works are found in literature that examine the flow field and the flow structures responsible for the generation of the drag. In cycling aerodynamics, Crouch et al. [5] conducted the first investigation that characterizes the large scale flow structures in the wake of a cyclist by balance measurements, flow and surface pressure measurements and flow visualizations. Crouch et al.’s work resulted in a better understanding of the flow structures generated by a complex bluff-body geometry as that of a cyclist on his bike. In line with the approach of Crouch et al., we propose to use large-scale tomographic Particle Image Velocimetry (PIV) for sport aerodynamics investigation.

The application of PIV for sport aerodynamics investigation is not new, even if only a limited number of studies are found in literature. As an example, Chabroux et al. [6] investigated the wake of different time trial helmets using stereoscopic PIV. Tomographic PIV (tomo-PIV) is an established technique for the quantitative visualization of three-dimensional flow fields. The review paper of Scarano [7] surveys the developments and main applications of tomo-PIV, which include flows around bluff bodies, turbulent wakes, boundary layers and transitional and turbulent jets. However, the measurement volume for air flows seldom exceeded 50 cm$^3$. More recently, Scarano et al. [8] discussed the use of helium-filled soap bubbles (HFSB) for large-scale tomo-PIV in wind tunnels. The use of HFSB as flow tracers made it possible to enlarge the measurement volume to 4800 cm$^3$. The HFSB enable the application of tomo-PIV on large scale, thus making tomo-PIV an attractive tool for aerodynamic investigation in speed sports.

Large-scale tomo-PIV is suitable for conducting on-site aerodynamic measurements via the ring-of-fire concept, which is illustrated in Figure 1. The ring-of-fire system consists of an enclosed volume where HFSB seeding particles are introduced. The tracers are illuminated by a laser or pulsed LED. Cameras record the tracer particles motion while the athlete passes through the tunnel. With respect to conventional wind tunnel measurements, the ring-of-fire is a versatile tool that enables aerodynamic measurements during the athletes’ training, so to reproduce with higher accuracy the flow conditions encountered in a race. The ring-of-fire concept is new in the sense that large-scale tomo-PIV is applied to a transiting object outside a wind tunnel.

The goal of this study is to prove the feasibility of the concept by using a scaled version of the ring-of-fire.

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Fig. 1. Illustration of the ring-of-fire concept
2 Experimental apparatus and procedure

2.1 Measurement system

Figure 2 shows an overview of the setup of the experiment. The scaled ring-of-fire consists of a tunnel, 170 cm long with a squared cross-section; the edge of the square is 50 cm. The tunnel is made out of wood and transparent Perspex to enable the optical access for both the illumination system and the digital cameras. Spheroids of different shape (sphere and conical aft) and size (8 and 16 cm diameter) are used as test models. The models transit through the tunnel at speeds between 0.7 and 1.35 m/s. The spheroid model is selected for two reasons: (1) The flow over a spheroid is comparable to the flow over an athlete in the sense that it is highly three dimensional and turbulent; (2) Spherical flow has been studied in detail in the past and is well documented in literature [9-12].

A Lego train transports the models through the tunnel. The models are mounted on the train by an aluminum rod, which is shown in Figure 2b. The trailing part of the rod is covered with an aerodynamic fairing to avoid flow separation and vortex shedding. Two wooden plates at the bottom of the tunnel separate the measurement domain from the influence of the Lego train. An opening between the two plates enables the rod with the spheroids to move through the tunnel. Brushes are mounted on the opening to prevent an upward air flow into the tunnel. Markers are attached to the spheroids to track their geometry on the camera images.

During each acquisition run, the train starts at a distance of about four meters from the entrance of the tunnel, which is about five meters from the measurement domain, in order to ensure that the wake behind the spheroid is fully developed by the time of image acquisition.

The tomo-PIV measurements are conducted using HFSB particles that are illuminated by a Quantronix Darwin Duo Nd:YAG laser (nominal pulse energy of 25 mJ at 1 KHz). Spherical lenses are used to increase the cross-section of the laser beam. The circular cross section is cut into a rectangular one via light stops at the top of the tunnel (Figure 2c). The measurement volume is equal to 20 (length) x 30 (height) x 16 (depth) cm³. The tunnel is seeded with HFSB particles (diameter ~ 300 μm) by a rake of ten nozzles that generate about 50,000 particles per second each. The seeding system (nozzles and a control panel that regulates the air, helium and soap fluid flow rates) is provided by LaVision GmbH. The imaging system consists of four Photron Fast CAM SA1 cameras (CMOS, resolution of 1024 x 1024 pixels, pixel pitch of 20 μm, 12 bit). Each camera is equipped with a 60 mm Nikkor lens set to f/22. The magnification is approximately 0.04. The PIV acquisition is performed within LaVision Davis 8.1. The acquisition frequency is 250 Hz.

2.2 Experimental procedure

Each acquisition run consists of the following steps:

1. The tunnel entrance and exit are closed to contain the HFSB seeding before the spheroid transits through the tunnel.
2. The HFSB nozzles run for two minutes to saturate the air with tracer particles. Afterwards they are shut down.
3. Since the HFSB nozzles have generated an air flow within the tunnel, a waiting period of about 30 seconds is required to achieve the condition of quiescent flow in the tunnel.
4. The tunnel entrance and exit are opened.
5. The model is put in motion through the tunnel.
6. The image acquisition is started as soon the spheroid is inside the tunnel.
7. 400 frames are stored. During this time, a translation of at least ten spheroid diameters is captured.
For each spheroid configuration, this procedure is repeated a number of times to achieve convergence of the statistical results. Because the acquisition procedure is time expensive, the number of acquired samples is limited.

3 Results

Figure 3a shows a sequence of three raw images taken by camera 1 of a spheroid with a diameter of 16 cm transiting through the tunnel. In this example the sphere moves with a velocity of $U_\infty = 1.1$ m/s. The interval between the images is 35 frames, which corresponds to 140 ms. The HFSB are clearly illuminated. The illuminated region is bounded by the rectangular cut at the top of the tunnel and by the shade of the sphere. Due to diffraction the particle image diameter is about 1.5 px. The estimated seeding density is above 0.05 particles/pixel.

The illumination distribution in z-direction is reconstructed by integrating the reconstructed particle intensity over an area of 175 x 275 mm$^2$ over a volume depth of -300 to 300 mm. Figure 3c presents the averaged distribution over 230 objects. In none of these objects the sphere was present. In the range of -80 to 80mm in volume depth the signal-to-noise ratio of the reconstruction is about 3.5.

The tomographic data analysis is performed in LaVision Davis 8.1 and consists of the following steps: (1) Image pre-processing (average subtraction and masking) is performed to eliminate background noise; (2) The fast MART algorithm is used for volume reconstruction on a discretized domain of 378 x 594 x 346 voxels; (3) The direct cross-correlation algorithm is applied on the subsequent reconstructed objects using correlation volumes of 64 x 64 x 64 voxels with an overlap of 75%. The output is a vector field with a density of 2.5 vectors/cm$^3$. No post-processing is applied on the resulting vector fields.

Figure 4 shows the instantaneous velocity field in x-direction in the center z-plane and the vorticity magnitude in the wake of the sphere at four time instants. At $t = 0$ the trailing point of the sphere is located at $x = 178$ mm, just outside the reconstructed volume. Each increment in time corresponds to a translation in space of 44 mm in positive x-direction. The main characteristic flow structures that are described in literature [11,12] are captured: (1) The wake extends about one sphere diameter from the sphere’s trailing edge; (2) A peak in the velocity field in x-direction is measured in the central area inside the wake; this peak corresponds to about 155 % of the sphere velocity (3) Backflow appears around the sides of the sphere; (4) Large-scale vortex structures are formed around the central wake area; (5) Velocity and vorticity magnitudes diffuse in time after the sphere has past. A detailed analysis of the results and comparison with literature will be conducted after the tomo-PIV analysis is refined and all recorded data sets are processed.

4 Conclusions

The ring-of-fire concept has been introduced to investigate the air flow over bluff bodies in motion. The system relies upon the use of tomo-PIV with HFSB as flow tracers. A scaled version of the ring-of-fire has been developed to provide a quantitative visualization of the three-dimensional flow field over a sphere with a diameter of 16 cm moving at 1.1 m/s. The results show that the ring-of-fire system is able to measure the characteristic flow structures that are reported in literature. In the next future, a quantitative comparison with the velocity fields reported in literature will be conducted to assess the accuracy of the ring-of-fire concept. Furthermore, instantaneous pressure reconstruction and determination of the drag force acting on the spheroids will be carried out [13].

References

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**Fig. 4.** Instantaneous velocity field in x-direction in the centre z-plane and the vorticity magnitude in the wake of the sphere at four time instants: (a) t = 0, (b) t = 40ms, (c) t = 80ms, (d) t = 120ms for a sphere velocity of 1.1 m/s. The three-dimensional iso-surface corresponds to a vorticity magnitude of 0.045 1/s.