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A quantitative flow visualization technique for on-site sport aerodynamics optimization

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Abstract

Aerodynamics plays a crucial role in many speed sports, where races are often won by fractions of a second. A thorough understanding of the flow field around an athlete is of paramount importance to optimize the athletes' posture, garment roughness and equipment shape to achieve the minimum aerodynamic drag and maximum velocity. To date, aerodynamic measurements are typically conducted in wind tunnels, using balances or pressure sensors. As a consequence, no information on the flow field responsible of the aerodynamic loads is gathered. Furthermore, the use of steady models yields a flow field that may differ significantly from that encountered during a race, where the athlete is in motion. The present paper proposes to use large-scale tomographic PIV for sport aerodynamic investigation. Helium-filled soap bubbles (HFSB) as flow tracers allow velocity measurements in a volume exceeding 10,000 cm^3, from which the aerodynamic loads can be computed. The technique is suitable for conducting on-site aerodynamic measurements via the *ring-of-fire* concept: the measurements are carried out during the athletes' training in a velodrome, thus reproducing the same flow conditions met during races.

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Keywords: Sport aerodynamics; particle image velocimetry; tomographic-PIV; large-scale PIV; helium-filled soap bubbles; ring of fire.

1. Sport aerodynamics and measurement techniques

The role of aerodynamics is critical in many speed sports as cycling, skating and bobsleigh. When a solid body moves through air, an aerodynamic force is produced. The latter is typically decomposed into lift, normal to the direction of motion, and drag, parallel to the direction of motion. Sætran and Oggiano [1] report that in speed

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skating, when the athlete reaches constant speed, the aerodynamic drag constitutes about 80% of the force the athlete has to overcome. In time trial cycling races, where the velocity is of the order of 14 m/s, the aerodynamic drag is more than 90% of the total resistance [2]. A decrease of the aerodynamic drag by 2% yields a reduction by 0.43 s of the race time on a 1 km time trial cycling race, where the world record is 56.3 s [2].

Aerodynamic investigation is required primarily for two reasons:

i. Optimization of the athletes' posture, garment and equipment shape to minimize the aerodynamic drag, thus achieving higher velocity;
ii. Enhancement of the directional stability to guarantee the athletes cornering capabilities and safety.

To date, sport aerodynamics investigation has been conducted mainly via computational fluid dynamics (CFD) simulations or wind tunnel tests around scaled models. Gibertini and Grassi [2] carried out wind tunnel force measurements to investigate the effect of the biker position on the aerodynamic drag. They found that the "time trial position" (head turned down and torso in horizontal position, aligned with the wind) yields a reduction of the drag area by almost 20% with respect to the "drops position", where the hands are on the drops portion of the handlebar. The same authors assessed that the position of the biker's head (up or down) influences the total drag by only 1%. Sayers and Stanley [3] studied the drag force on rotating cycling wheels. From their wind tunnel measurement, they concluded that fully cladded wheels feature a lower drag coefficient by 40% than spoked wheels. Conversely, partial cladding of the wheel yields little to no improvement. Furthermore, Kyle and Weaver [4] report a thorough discussion on the aerodynamic design of racing bicycles. The effect of the skin suit on speed skating aerodynamics has been investigated by Sætran and Oggiano [1] by wind tunnel force measurements. The drag of six suits has been assessed in the range of speeds from 8 m/s to 18 m/s. The authors highlight that the same suit may have different performance when used by men or women due to the different size of legs and arms, which triggers the transition from laminar to turbulent boundary layer at different speeds. Dabnichki and Avital [5] made use of a simplified computational model and wind tunnel force measurements to assess the influence of the crew position on the aerodynamic performance of bobsleigh. The results produced two major findings: a) bending forward by the brakewoman is beneficial for reducing the pressure drag; b) narrowing the cavity reduces considerably the pressure drag.

The behavior of an athlete and his/her equipment in an air flow is comparable with that of a bluff body: the air flow separates from the surface of the object producing a large turbulent wake. The determination of the flow field via CFD simulations relies upon the introduction of turbulence models to predict the effect of turbulence. As a consequence, for sport aerodynamics the accuracy of CFD simulations is often questionable and validation experiments are required. Conversely, wind tunnel tests allow a direct measurement of the flow field or the aerodynamic forces. However, most of the measurements for sport aerodynamics are "blind", because obtained with pressure or force sensors, which do not provide information on the flow features producing the aerodynamic loads. Furthermore, a steady model is often used, giving little information on the actual aerodynamics occurring during competitions, when the athlete is in motion.

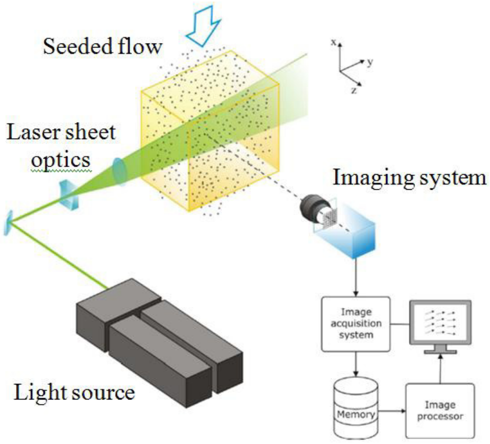

Fig. 1. Setup of a PIV experiment. Illustration reproduced from [7].

Particle image velocimetry (PIV) is an experimental technique that allows measuring the flow velocity in a two- or three-dimensional domain. Micrometric particles are added to the flow and carried by the fluid. The particles are illuminated twice by a light source, typically a laser, and imaged by a digital camera. The images are then analyzed to determine the particle displacement within the short time interval between two successive laser pulses. The ratio between displacement and time interval yields the velocity field in the imaged region [6]. Figure 1 illustrates the typical setup of a PIV experiment.

PIV is nowadays considered a standard tool for the investigation of turbulent flows. One of the advantage with respect to pressure or force measurements is that it is a quantitative flow visualization technique: the velocity field is measured, from which pressure field and aerodynamic forces can be retrieved. As a consequence, PIV allows a thorough understanding of the flow features responsible of the aerodynamic forces acting on a body.

Tomographic PIV (shortly tomo-PIV) is an evolution of the standard planar PIV that allows measuring the velocity field in a three-dimensional domain. The particles are illuminated in a volume and imaged by several cameras at different viewing angles. The images acquired are processed to reconstruct the 3D spatial distribution of the tracer particles; this additional step with respect to planar PIV is named *volume reconstruction*. Although tomo-PIV has been applied in several wind tunnel experiment, the typical measurement volume seldom exceeds 50 cm^3 [8]. The main factors limiting the upscale of tomo-PIV to larger volumes are the limited pulse energy of the light source, the scattering efficiency of the tracers and the sensitivity of the imagers. While the sensor technology has significantly increased in the last years, the technology of PIV lasers and seeding system has essentially remained the same. In tomo-PIV, the intensity of the illumination is typically an order of magnitude smaller than that of planar PIV due to the expansio the laser beam over a large cross-section. As a result, the light intensity recorded by the cameras drops dramatically with increasing the measurement volume.

Helium-filled soap bubbles (HFSB) have been proposed as flow tracers for large-scale tomo-PIV wind tunnel experiments by Scarano *et al* [9]. In the present work, the HFSB production system is discussed and the application of the technique to the flow around a vertical-axis wind turbine (VAWT) is presented. Finally, the ring-of-fire concept for on-site sport aerodynamics measurements is introduced.

2. Large-scale tomographic PIV with helium-filled soap bubbles

2.1. Helium-filled soap bubbles generator

The HFSB generator has been developed at the German Aerospace Center (DLR) and used for several PIV experiments in buoyant flows [10]. The generator is composed by two coaxial channels terminating with a small circular orifice. It is fed by constant flow rates of helium, bubble fluid solution (BFS, a mixture of water, glycerine and soap) and air (see figure 2). The generator produces bubbles of diameter of approximately 300 μm, which are much larger than standard PIV seeding (1 μm diameter). A picture of the HFSB is shown in figure 3. As a result of the greater size, the light intensity scattered by the HFSB is larger by over an order of magnitude. Furthermore, by tuning the flow rates of BFS (heavier than air) and helium (lighter than air), neutrally buoyant bubbles can be produced.

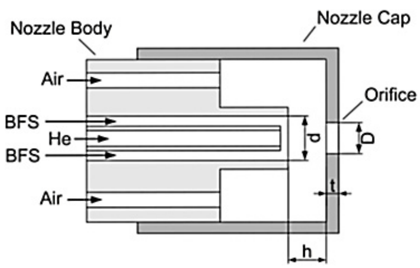

Fig. 2. Schematic representation of the HFSB generator. Illustration reproduced from [10].

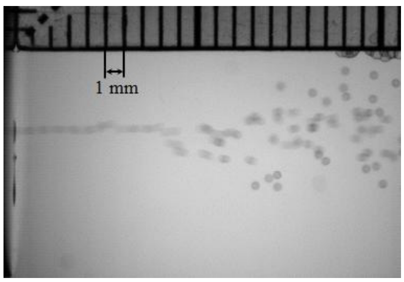

Fig. 3. Picture of the HFSB produced by a nozzle.

The flow tracking capability of the HFSB has been assessed by Scarano *et al* [9] comparing the velocity in a potential flow measured with the bubbles and with micron-sized flow particles. The authors found a characteristic response time for the HFSB of the order of 10 μs, which makes them suitable for PIV experiments in subsonic flows.

2.2. Application to the flow around a vertical-axis wind turbine

The HFSB system was used to investigate the near wake of a vertical-axis wind turbine (VAWT). The experiments were conducted in the Open Jet Facility (OJF) of TU Delft, which is a closed-circuit open-jet wind tunnel with an octagonal test section of 2.85 m × 2.85 m. The wind tunnel is powered by a 500 kW electric fan, thus allowing a free-stream velocity from 3 m/s to 34 m/s. The maximum turbulence intensity is 0.5%. The model is the two-blade H-shaped rotor VAWT of 1 m diameter (D) used by Tescione *et al* [11] for their experiments. The rotor blades have a NACA0018 aluminum profile of chord $c = 0.06\ D$. The blade span is $H = 1$ m, yielding an aspect ratio $AR = H/D = 1.0$. Measurements were conducted at free-stream velocity $V_\infty = 8.5$ m/s and rotational speed $\Omega = 127$ rpm, yielding a tip speed ratio $\lambda = 5$. The Reynolds number based on the blade chord was $Re_c = 32{,}000$.

The illumination was provided by a Quantronix Darwin Duo Nd:YLF laser, which had a nominal pulse energy of 25 mJ at 1 kHz. The laser beam was shaped into a rectangular cross section by means of laser sheet optics and beam cutters. Images were acquired with three Photron Fast CAM SA1 cameras (CMOS sensor, 12-bit, 1,024×1,024 pixel resolution, pixel pitch of 20 μm) positioned at the side of the VAWT. The cameras were equipped with Nikkor lenses of focal length $f = 60$ mm. The lens aperture of $f/11$ allowed focused particle images over the entire measurement domain. The measurement volume of 35×21×17 cm^3 was positioned in such a way to study the dynamics of the blade tip vortex when the blade passes from the windward position (chord of the blade aligned with the free-stream velocity, with the wind tunnel flow directed from leading edge to trailing edge of the blade) to upwind position (blade closest to the wind tunnel jet exit). The optical magnification factor was $M = 0.06$, the sampling rate was 1 kHz.

The seeding was provided by a helium-filled soap bubbles nozzle. A single generator produces bubbles at a rate of about 50,000 bubbles/s, which would yield an insufficient seeding concentration for PIV experiments. In order to increase the bubble production rate, a seeding concentration enhancement system was design and developed [9]. The system was based on a piston-cylinder device. HFSB were stored in the cylinder during the *accumulation phase*, when the piston was moving outward to increase the available volume. The duration of the accumulation phase was about 60 seconds. In the *release phase*, the piston moved quickly inward in about 1 s. A duct allowed transporting the stream of HFSB into the test section, where an aerodynamic injector was placed. The latter was composed by 12 airfoils divided in two rows of 6 each. Each airfoil featured 22 orifices at the trailing edge that allowed releasing the HFSB stream into the test section. A picture of the experimental setup is shown in figure 4. The piston-cylinder system allowed a nominal increase of the bubbles production rate equal to the ratio between accumulation and release times, that is by a factor 60. The seeding concentration achieved in the test section was about 2 bubble/cm^3.

An instantaneous velocity field is shown in figure 5. The origin of the coordinate system is at the trailing edge of the blade when it reaches the windward position. The free-stream velocity is directed along x from negative to positive values. The flow field shows the presence of tip vortices due to the pressure difference between suction and pressure sides of the blade. The vortices visualized in the domain are generated during the motion of the blade from the windward to the upwind position. Two vortices are distinguished, having diameter of about 8 mm: an upstream vortex at $x<0$ and a downstream vortex at $x>0$ which is generated by the passage of the preceding blade and is convected downstream at the free-stream velocity. The vortex is generated at the blade tip, that is at $z = 0$ mm; however, when it reaches the edge of the measurement domain ($x = 150$ mm), it is located at $z \cong 50$ mm, which indicates the presence of a downward velocity induced by the blade. In the measurement domain, the peak vorticity decreases by 15% along the streamwise direction (from 270 rad/s at $x = -100$ mm to 230 rad/s at $x = 150$ mm): this result suggests that dissipation effects are negligible within the a distance smaller than half the propeller radius, which is consistent with the results reported in [11].

The vortex shedding frequency, computed from the power spectrum of the vertical velocity at a point of the flow field (namely (x, y, z) = (-75 mm, -15 mm, 10 mm)), is equal to 27 Hz, which agrees with twice the rotation frequency of the two-blade turbine. The latter result confirms the capability of the system of measuring the vortex shedding phenomenon occurring at the blade tip.

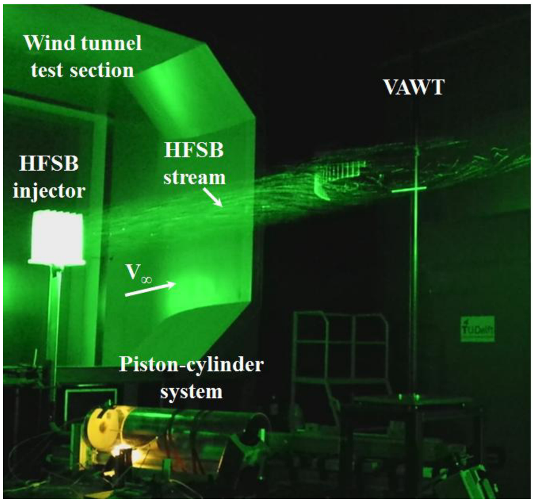

Fig. 4. Picture of the experimental setup for the VAWT experiment.

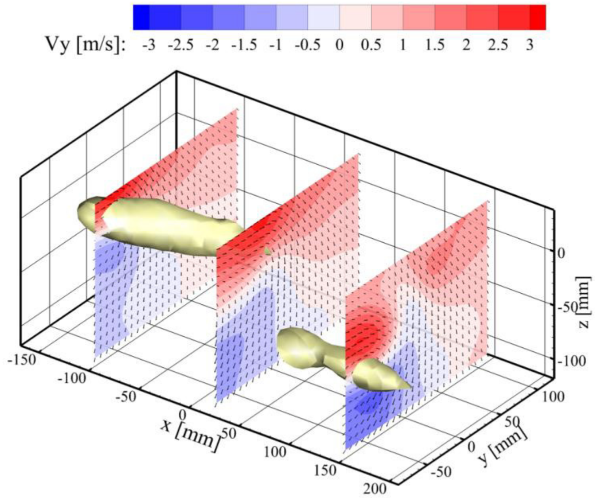

Fig. 5. Instantaneous velocity field. Isosurface of vorticity magnitude ω = 180 rad/s.

3. The ring-of-fire concept

Section 3 has shown that large-scale tomographic PIV with helium-filled soap bubbles allows conducting aerodynamic measurements in a three-dimensional domain of volume exceeding 10,000 cm^3. The use of high-speed cameras and lasers permits acquiring data at sampling rate of several kilohertz, thus resolving the evolution of flow features in time. Furthermore, making use of the flow dynamics equations, pressure field and aerodynamic loads acting on a body can be retrieved from the velocity.

Large-scale tomo-PIV opens unprecedented possibilities for sport aerodynamics investigation. First, non-intrusive pressure and force measurements can be conducted without the installation of sensors or transducers on the model. Secondly, the measurements allow a quantitative visualization of the flow field, thus relating flow features (e.g. flow separation, wake, vortical structures, boundary layer characteristics) with the measured aerodynamic loads. Furthermore, the technique is suitable for conducting on-site aerodynamic measurements. The measurement system can be installed in a chamber integrated in a training track. Light is provided e.g. from the top of the chamber by a laser or LEDs, thus producing the *"ring-of-fire"* the athletes pass through during their training. Helium-filled soap bubbles are released by an injector before the athlete passes through the ring of fire and images of the tracer particles are acquired by digital cameras in tomographic configuration. A schematic representation of the ring-of-fire in a velodrome, an indoor cycling track, is shown in figure 6.

The ring-of-fire concept has clear advantages for sport aerodynamics investigation: first of all, it allows conducting aerodynamic measurements during the athlete's motion, which is a major improvement with respect to considering steady models as it is typically done in wind tunnel tests or numerical simulations. Furthermore, the ring-of-fire would be an effective way to investigate the aerodynamic forces generated during cornering, which is not feasible neither with wind tunnel tests nor with numerical simulations. Of course, the integration of the ring-of-fire into a sport facility requires considerations on minimal intrusiveness, safety regulations and interaction with surrounding structures which are currently under investigation.

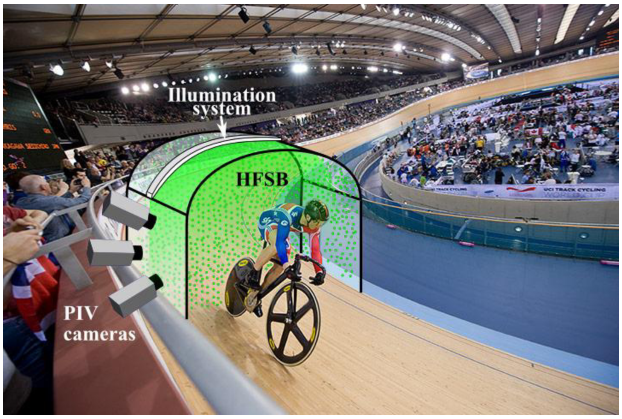

Fig. 6. Schematic representation of the ring-of-fire concept for on-site aerodynamic measurements in a velodrome.

4. Conclusions

The work presents an innovative technique for on-site measurements for sport aerodynamics. The technique is based on tomographic-PIV, where the motion of small tracer particles inserted into the flow is measured to retrieve the velocity field in a three-dimensional domain. The use of sub-millimeter helium-filled soap bubbles (mean diameter of 300 μm) as tracer particles allows increasing the measurement volume from 50 cm^3 [8] to over 10,000 cm^3. The application in the wind energy sector has shown the capability of the technique to measure the dynamics of the tip vortex generated by a vertical axis wind turbine. For sport aerodynamics, the use of large-scale tomo-PIV with HFSB would allow measuring the flow field around an athlete or details of his/her equipment (e.g. a helmet), thus relating the aerodynamic loads with the flow features responsible of those. The measurements could be used to optimize the athletes' posture, garments roughness and equipment shape to minimize the aerodynamic drag and maximize the athlete's velocity. Finally, the technique is suitable for conducting on-site aerodynamic measurements via the *ring-of-fire* concept: the measurements are carried out during the athletes' training in a velodrome, thus reproducing the same flow conditions encountered during races.

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