Annual Report 2022 JMBC – Research Highlight

**This highlight refers to the PhD Thesis by Alexander Spoelstra (2022)**

# Ring of Fire as a novel approach to study cycling aerodynamics

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In many speed sports such as cycling or skating, aerodynamic drag constitutes up to 90% of the total resistance an athlete has to overcome. Understanding the physical mechanisms responsible for the production of the aerodynamic drag is key to maximize the athlete's performance, hence providing them with a competitive advantage. The research conducted in this PhD project introduces a new measurement concept for on-site aerodynamics investigation based on large-scale stereoscopic particle image velocimetry (stereo-PIV) measurements past an athlete, a vehicle or an object travelling through a quiescent environment (Spoelstra, 2022). The analysis of the momentum deficit past the transit poses the basis to estimate the aerodynamic drag. Such an approach, where the object crosses the illuminated measurement plane, is referred to as "Ring of Fire". The measurements are conducted with cyclists both in in-door and out-door environments (Spoestra et al. 2019, 2021a), skaters (Spoelstra et al., 2023) and road vehicles (Huetting et al., 2023). The effect of drafting in cycling is also investigated (Spoelstra et al., 2021b), assessing the aerodynamic benefit of the trailing rider depending on their lateral and longitudinal offset with respect to the leading rider. This document provides a concise overview of the working principle and main results of the Ring of Fire concept.

## Working principle of the Ring of Fire concept

In this section, the Ring of Fire concept is explained for the analysis of the flow field and aerodynamic drag of a moving cyclist; however, the conclusions can be extended to other problems such as speed sports in general and ground vehicles. In contrast to typical wind tunnel conditions where the cyclist is at rest, in the Ring of Fire the cyclist is in motion, transiting through a fixed measurement plane (i.e. the laboratory frame of reference, $R = \{X',Y',Z'\}$ in Figure 1). A control volume centred at the cyclist location is considered to move with the cyclist ($R = \{X,Y,Z\}$ in Figure 1) at constant cycling velocity $u_C$ with respect to the laboratory frame of reference.

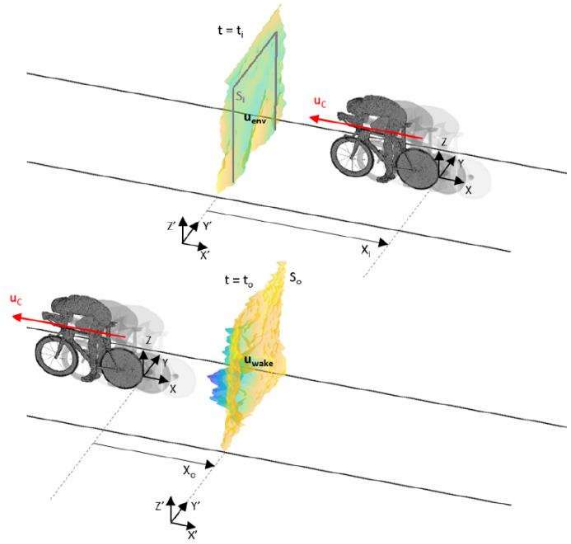

*Figure 1. Control volume approach in the Ring of Fire concept: upstream flow ($u_{env}$) measured at ti, downstream flow ($u_{wake}$) at to.*

The air motions prior to the passage of the cyclist feature a chaotic velocity $u_{env}$ resulting from the environmental effects. After the passage of the cyclist, the flow velocity features a coherent wake with a velocity distribution, $u_{wake}$, which follows the moving cyclist. By writing the conservation of momentum in a control volume enclosing the cyclist, the cyclist's aerodynamic drag can be retrieved:

$$D(t)=\rho\iint_{S_i}\left(u_{env}-u_C\right)^2 dS+\rho\iint_{S_i} p_i dS-\rho\iint_{S_o}\left(u_{wake}-u_C\right)^2 dS-\rho\iint_{S_o} p_o dS \tag{1}$$

where $\rho$ is the fluid density, $p_i$ and $p_o$ are the static pressures before and after the passage of the cyclist, respectively. Equation (1) is valid at the condition that the mass flow is conserved across the inlet and outer surfaces $S_i$ and $S_o$, respectively. Ensemble-averaging equation (1) in time and across multiple passages of the rider provides the ensemble-average aerodynamic drag of the cyclist.

A large-scale stereoscopic Particle Image Velocimetry (PIV) system is employed for the measurement of the flow velocity prior and after the passage of the rider. Neutrally-buoyant helium-filled soap bubbles (HFSB) of 300 µm median diameter are used as flow tracers due to their large scattering cross section. The HFSB are illuminated by a pulsed laser (Nd:YAG or Nd:YLF) and images are acquired via digital cameras (typically CMOS or sCMOS). An example of experimental arrangement for Ring of Fire measurements is reported in Figure 2 (Spoelstra et al., 2019).

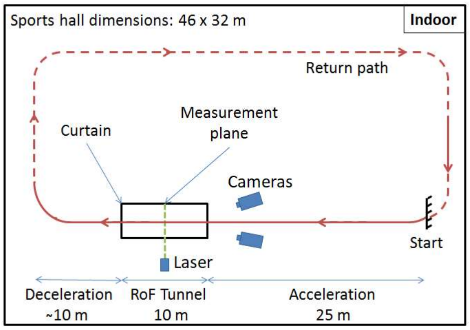

*Figure 2. Example of experimental arrangement for indoor Ring of Fire measurements for cycling aerodynamics.*

In the following, the streamwise velocity component and time are expressed in non-dimensional units as follows, considering the athlete's torso chord length *c* = 600 m as reference length:

$$u_x^* = \frac{u_{wake} - u_{env} - |u_C|}{|u_C|}; \qquad t^* = \frac{t \cdot |u_C|}{c}. \tag{2}$$

## Application to cycling

Some of the results of the indoor and outdoor measurements for cycling aerodynamics are shown here, with the rider in the upright and time-trial configurations. The temporal development of the ensemble average streamwise velocity field $\overline{u_x^*}$ past the cyclist is shown in Figure 3. The ensemble average is obtained from 28 and 10 individual runs from the indoor and outdoor experiments, respectively. The maximum deficit in the wake (~45%) is observed at the shortest time delay after the passage. The deficit is not uniformly distributed and attains its maximum behind the legs. The turbulent diffusion causes a rapid redevelopment of the flow in the wake. The flow entrainment smoothens the fine details of the streamwise velocity distribution and, internally to the wake, the peak velocity deficit reduces. The diffusion process causes the wake to exceed the measurement region, with consequences on the uncertainty of the drag estimate. This occurs earlier for the outdoor experiment (*t** ~ 9) than for the indoor experiment (*t** ~ 13), which is ascribed to the higher intensity of the velocity fluctuations in the surrounding environment.

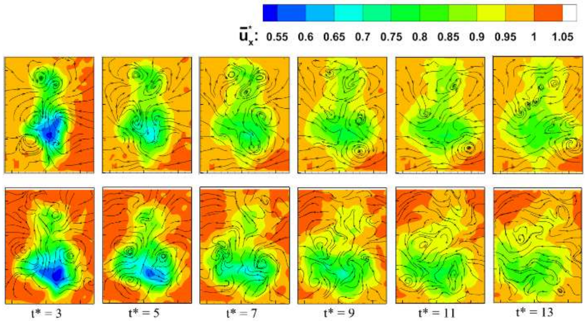

*Figure 3. Development over time of the dimensionless ensemble average streamwise velocity behind the cyclist in time-trial position. Indoor experiment (top) and outdoor experiment (bottom).*

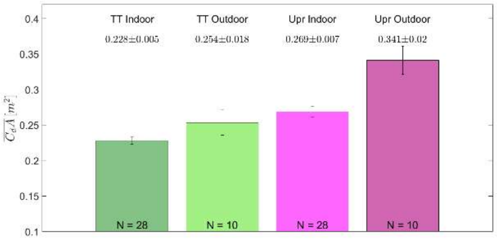

*Figure 4. Ensemble-average drag area for the different cyclist postures (time-trial and upright) and measurement conditions (indoor and outdoor); uncertainty bars for 95% confidence interval. N indicates the number of cyclist's passages per case.*

The evaluation of the cyclist's drag area, illustrated in Figure 4, shows that the time-trial position leads to a reduction of the aerodynamic drag by up to 35% compared to upright position, which is in agreement with literature. Additionally, the drag areas in the outdoor experiment were found higher than in the indoor experiments, which is ascribed to differences in the rider's postures and frontal areas and in the environmental conditions.

**Application to speed skating**

Experiments were performed in February 2021 in the ice-rink of Thialf in Heerenveen, the Netherlands, to investigate the effect of skater's posture on the aerodynamic drag. Two athletes transited through the Ring of Fire 20 times each, 10 times in each skating configurations. The configurations investigated were: two arms on the back versus one arm on the back and one loose; low trunk versus high trunk postures. All tests were performed at a nominal skating speed of 11 m/s. The experimental setup, illustrated in Figure 5, consisted of two high-speed CMOS cameras recording images of the HFSB tracers, illuminated by a Nd:YLF pulsed laser and confined within a tunnel of 10×13×3 $m^3$.

The average streamwise velocity fields measured 0.5 m behind the lower back of the skater for the low trunk and high trunk postures are shown in Figure 6. The streamwise velocity contours clearly show two different shapes, thus indicating a strong dependence on the skating posture. The near wakes of the two configurations clearly exhibit similar streamwise velocity contours; nevertheless, the wake of the low trunk posture is shorter. Both contours show the strongest velocity deficit behind the trunk and upper legs and some smaller velocity deficits behind the extended (right) arm and (left) leg. The wake of the high trunk posture features slightly higher velocity deficits ($u_x^* < 0.4$) compared to the wake of the low trunk posture ($u_x^* = 0.5$). From the analysis of the momentum deficit in the control volume enclosing the athlete, it was found that skating with low trunk angle resulted in a statistically significant drag reduction by 7.5% compared to skating with high trunk angle. Instead, the difference in drag area between skating with both your arms on the back or with just one arm on the back was not statistically significant.

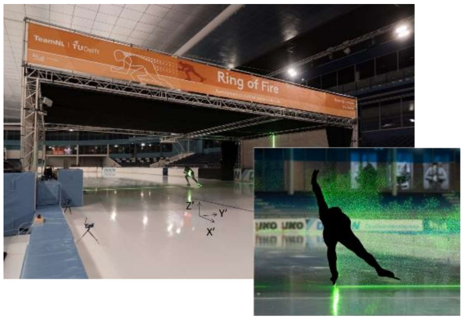

*Figure 5. Ring of Fire setup in the skating rink of Thialf, the Netherlands. An athlete skating through a cloud of helium filled soap bubbles illuminated by laser light.*

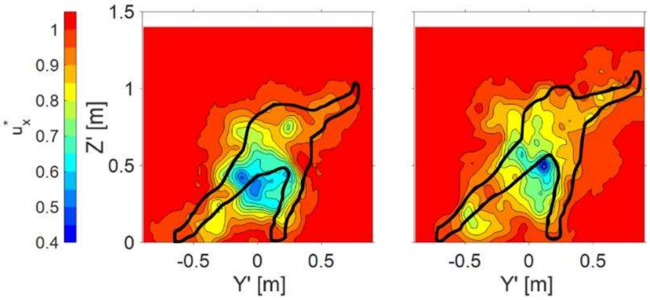

*Figure 6. Average streamwise velocity $u_x$* at X = 0.5 m for the skater in low trunk posture (left) and high trunk posture (right).*

## Conclusion and outlook

A new measurement concept has been introduced for the investigation of the wake flow and aerodynamic drag of transiting objects such as sports athletes and ground vehicles. The measurement system relies upon the use of stereoscopic PIV, whereby neutrally-buoyant sub-millimeter helium-filled soap bubbles (HFSB) are used as flow tracers to capture the wake dynamics over planes of the size of several square meters. The application of the conservation of momentum in a control volume enclosing the transiting object allows the determination of the object’s aerodynamic drag. The measurement system has been assessed experimentally for cycling aerodynamics in both indoor and outdoor conditions, as well as for skating aerodynamics, shedding light on the aerodynamics of these sports and the physical mechanisms responsible for drag variations in different configurations of the athletes. A dedicated study of the drag resolution of the Ring of Fire system showed that the uncertainty of the average drag measurements is currently within 5%. Although such value is considered rather coarse when compared with state-of-the-art force balance measurements conducted in a wind tunnel, it shows great potential for a range of applications, such as drones, cars, trains and birds, due to the possibility to determine the aerodynamic drag in-field rather than in the lab environment. Future applications are envisaged in the automotive and UAV sectors, both to increase the understanding of the flow physics and for the generation of experimental databases for the validation of numerical simulations.

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## VIDEOS

NWO video on the Ring of Fire project

Video on the Ring of Fire in the ice-rink of Thialf (in Dutch)

TU Delta TV video on the Ring of Fire for cycling aerodynamics