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The Ring of Fire for on-site cycling aerodynamics

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Abstract

Low-speed aerodynamics plays an important role in numerous applications in cycling, where significant improvements in performance and efficiency can be achieved by aerodynamic optimization. Cycling is a unique case within bluff body aerodynamics due to the complex and dynamic geometry of an athlete. Understanding how the flow behaves around an athlete is critical to the performance because aerodynamic drag is the dominant form of resistance acting on a cyclist, even at speeds as low as 15 km/h. As a result, over the last few decades there has been a considerable amount of research dedicated to the influence of posture and equipment on the drag of a cyclist, as this has specific performance applications.

Several approaches for measuring the aerodynamic forces, particularly drag, have been proposed in the past, including wind tunnel measurements (Zdravkovich, 1996), on-site measurements (Edwards et al., 2007) and numerical simulations by computational fluid dynamics (CFD) (Defraeye et al., 2010). Wind tunnel measurements are very accurate and repeatable; however, they often struggle to simulate realistic conditions due to the dynamical situation to be simulated (e.g. a cycling or running athlete), the ground effect or the scale of the object (Barlow et al., 1999). A higher level of realism in the experimental conditions can be obtained by track tests. In recent years, the steady-state torque test has become the most practiced method for track testing in cycling. Power meter measurements are carried out to determine the cyclist's aerodynamic drag based on the balance of power (Grappe et al., 1997). The advantages over wind tunnel measurements of more realistic flow conditions and lower costs are counterbalanced by an increased uncertainty deriving from additional error sources, such as the less-controlled atmospheric conditions and the physical modelling of non-aerodynamic resistance forces, e.g. due to rolling resistance and drive train losses. Alternatively, when the primary interest of the research is the flow visualization, the investigation can be conducted by means of computational fluid dynamics (CFD) simulations. Advancements in meshing and turbulence modelling in recent years have made CFD a popular method of investigating cycling aerodynamics (Griffith et al., 2014). CFD simulations have several clear advantages. They allow full control of the cyclists' posture, as well as of the incoming flow properties; furthermore, they provide both the aerodynamic drag and the flow field around the cyclists. However, when applied to three-dimensional unsteady flows such as those around athletes, these simulations often suffer from low accuracy and require validation experiments.

Where cycling is concerned, there seems to be an important disconnection in conventional methods of aerodynamic analysis (wind tunnel, CFD and track tests) between quantitative drag determination, flow field visualization and reproducibility of realistic conditions. Sciacchitano et al. (2015) therefore introduced a new measurement concept, the Ring of Fire (RoF), that enables the aerodynamic drag estimation of transiting cyclists. The approach relies upon the use of large-scale stereoscopic particle image velocimetry (PIV) measurements over a plane crossed by the cyclist during motion. The momentum before and after the passage of the cyclist poses the basis for the control volume analysis in the vehicles frame of reference, which returns the aerodynamic drag.

The first Ring of Fire experiment was conducted by Terra et al. (2017), who performed a proof-of-concept study on a towed, 10 cm diameter sphere. The authors found that the time-average drag coefficient of the model falls within the range of reported values in literature and that the estimation of the drag coefficient is unaffected by the measurement position in the wake. Furthermore, they observed that the pressure term in the momentum balance vanishes after 5 diameters, which can greatly simplify the measurement procedure. In order to assess the practical implementation and accuracy of the proposed technique on a full scale, Spoelstra et al. (2019) conducted 2 experiments with a cyclist riding through a duct in time-trial and upright position: an indoor and an outdoor one. Despite differences between the two experiments in the cyclist geometry, bike model and the cycling speed, the flow topology in the near wake of the riders compared well between both experiments and to literature. The drag area of the different cases exhibited a constant value along the wake, with an uncertainty of 5%, indicating the suitability of the RoF for aerodynamic analysis and optimization studies. The comparison of drag values with literature data, however, could not yield a conclusive assessment, given the large dispersion (approx. 50%) of the data due to many varying parameters, like rider posture, bikes geometries and testing conditions. However, a clear distinction in upright vs. time trial time aerodynamic drag is found for both experiments, with the upright posture yielding higher drag area by about 20-35% with respect to the time trial posture. Although the previous RoF experiments had returned wake measurements that agree satisfactorily with wind tunnel data, the uncertainty of the measured drag and its dependency upon experimental conditions and the image processing parameters was still unclear. Alexander Spoelstra et al. (2020) showed that applying a dedicated wake contour and imposing the conservation of mass results in the most accurate drag measurements. Additionally, in this work the drag values obtained with the RoF were compared against the drag estimates from simultaneously acquired power meter data. To assess the agreement between the two approaches in different regimes, three individual tests were performed where small drag variations due to different helmets as well as large drag variations due to different cyclist postures were produced. Regardless of the underlying input parameters in the power meter model, both small- and large scale deltas were well captured by both the RoF technique and the power meter approach and agreed with available literature values (Barry et al., 2014). The uncertainty on the average drag measurements from the RoF was again within 5%. All preceding studies

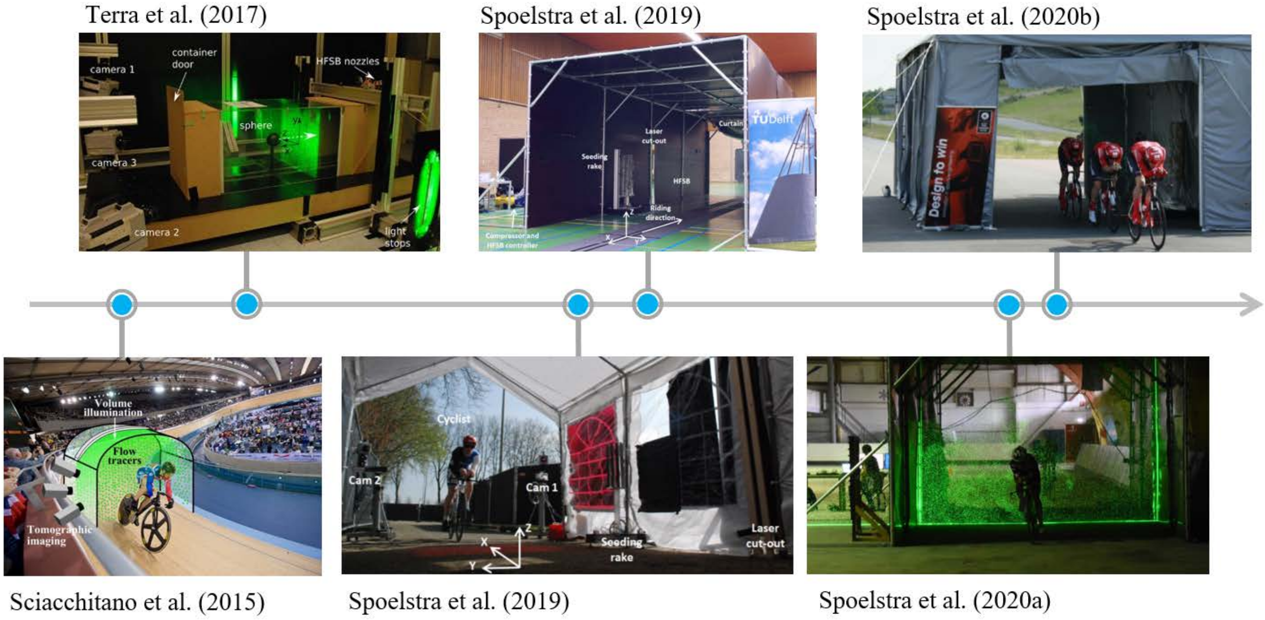

Fig. 1 Overview of different Ring of Fire experiments.

showed to provide the aerodynamic drag of an individual cyclist during sport action and returned a quantitative visualization of the flow field in the wake. Thanks to the ability to measure the flow field in the wake of a cyclist, as well as the posture and the relative distances between riders, the Ring of Fire system is in principle also suited for the investigation of the aerodynamics of a group of riders. For this reason, in the most recent work, the RoF system was deployed to evaluate the effects of cyclists' position and their relative size on the aerodynamic drag (A. Spoelstra et al., 2020). The longitudinal and lateral separations of the drafters varied respectively between 0.35 m and 0.85 m and between ±0.20 m among different runs. The savings for the drafting cyclist in this spectrum range from 27% to 66%. It was found that the aerodynamic advantage decreases as lateral and longitudinal separation between riders is increased, where the lateral distance is found to be more relevant. Furthermore, it was observed that the larger the isolated drag area of the leading cyclist is, the larger the benefit for the drafting cyclist. Besides these results, the RoF also showed great potential to simultaneously give an indication of the drafting skill level of cyclists, which is infeasible with the current state-of-the-art measurement techniques for cycling aerodynamics. An overview of all the RoF experiments can be seen in Fig. 1.

Over the past few years the RoF system has become a reliable measurement system that enables the user to relate the drag force to the velocity distribution in the wake of the test object. The results discussed here indicate the suitability of this principle for aerodynamic analysis and optimization studies and potential upscaling for applications in other sports or industries.

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