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Analysis of crosswind aerodynamics for competitive hand-cycling

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ABSTRACT

Competitive hand-cycling represents a unique case for cycling aerodynamics as the athletes are in a relatively aerodynamic position in comparison to traditional able-bodied cyclists. There are some aerodynamic similarities between both cycling disciplines, including wheel designs and helmets. The lack of research in hand-cycling aerodynamics presents the potential for significant improvements. This research analysed the aerodynamics of competitive hand-cycling under crosswind conditions using wind-tunnel experiments and Computational Fluid Dynamics (CFD) simulations. A range of yaw angles from 0° to 20° in 5° increments were investigated for two separate hand-cycling setups; a road race and a time-trial setup. A maximum drag increase of 14.1% was found from 0° to 15° yaw, for a hand-cyclist equipped for a road race. The three disk wheels used for the TT setup had a large impact on the lateral forces experienced by the TT hand-cyclist. At just 5° yaw and at 15 m/s, the drag and lateral forces for the TT setup matched closely, while this event did not occur until 15° yaw at the same velocity for the road setup. For 20° yaw, the ratio of the lateral force to drag force was 1.6 and 5.6 for the road and TT setups respectively.

1. Introduction

Crosswinds can be a hindrance for cyclists across all cycling disciplines. Race tactics have been developed to counter crosswind effects, such as riding in staggered formations. In addition to the drag dependence on yaw angle, another important aspect in crosswind conditions is that disk wheels can affect stability and steering (Crouch et al., 2017; Tew and Sayers, 1999). Contrary to aerofoil aerodynamics, the drag experienced by a cyclist is measured in the direction the cyclist is travelling as opposed to the stream-wise flow direction (Barry et al., 2012; Fintelman et al., 2014, 2015a).

Aerodynamic refinement is commonly the subject of scientific investigations for improved performance in cycling (Haake, 2009), with cyclist postures having received significant attention in the literature (Defraeye et al., 2010a; Fintelman et al., 2015b; García-López et al., 2008). However, crosswind analysis of able-bodied traditional cyclists has seen limited attention in the literature, even though cyclists typically experience a crosswind to some degree in all outdoor events. Concerning traditional cycling, Fintelman et al. (2015a) performed Computational Fluid Dynamics (CFD) simulations to analyse solo cycling aerodynamics under crosswind conditions, with validation data acquired from wind-tunnel experiments described by Fintelman et al. (2014). It was found that Large-Eddy Simulation (LES), by comparison to the wind-tunnel experiments, provided the best performance for drag prediction for 15° yaw with a deviation of 5%. Larger discrepancies were found by Fintelman et al. (2015a) between experimental and numerical results using other methods such as Detached Eddy Simulation (DES), with deviations from the experimental data of up to 17% between the drag forces at yaw angles of 15°.

The majority of the crosswind aerodynamics studies in cycling have focused on isolated wheel geometries (Barry et al., 2012; Godo et al., 2010; Tew and Sayers, 1999). Wind-tunnel experiments were conducted by Tew and Sayers (1999) to compare a number of wheel selections over a variety of yaw angles (0°–30°), wind speeds (30–55 km/h) and rotational velocities (corresponding to 0–55 km/h linear velocities). At 0° yaw, the drag by the disk wheel was 70% lower than for the standard spoked wheel. However, the standard thirty-six shallow rim spoke wheel had significantly lower lateral force coefficients than the other five

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wheels tested. The disk wheel experienced a reversal in the lateral force direction (perpendicular to the direction of motion) from negative to positive in the region of 0°–8° yaw for all wind speeds, indicating a shift in the location of boundary layer separation. Godo et al. (2010) considered six isolated wheel geometries over 10 yaw angles at two velocities: 20 mph (32.19 km/h) and 30 mph (48.28 km/h). The disk wheel provided the greatest drag advantage, with the deep dish wheel in second place. However, both wheels experienced lateral forces in excess of all other wheels tested.

Wind-tunnel testing and CFD simulations have been used extensively for cycling aerodynamics and other competitive sports topics (Blocken, 2014; Crouch et al., 2017). However, to the best of our knowledge, a detailed analysis of crosswind effects on hand-cycle aerodynamics by either CFD simulations or wind-tunnel tests has not yet been published. Crosswinds can be important for performance and safety. This paper analyses the crosswind aerodynamics for a H3 category competitive hand-cyclist in a road race setup (Fig. 1a,c) and time-trial setup (Fig. 1b, d), which is relevant for categories H1-H4 due to the athlete positions adopted and the cycling equipment (UCI, 2017).

2. Wind-tunnel experiments

Wind-tunnel experiments were carried out in the aeronautical test section of the wind-tunnel laboratory at the University of Liège, Belgium, in a test chamber with cross-section dimensions $2 \times 1.5\,\mathrm{m}^2$. A H3 competitive hand-cyclist was 3D scanned to provide the geometrical data for manufacturing a quarter-scale model (Fig. 2a). The blockage ratio reached 2.3% at the maximum yaw angle of 20°. The cyclist model was placed on a smooth horizontal platform with a sharp leading edge and raised 0.3 m from the test chamber floor to reduce the approach-flow boundary layer height (Fig. 2b). A wind speed of 60 m/s was imposed for Reynolds number similarity with a full-scale hand-cyclist at 15 m/s. 3D solid blockage corrections from (Barlow et al., 1999) applicable for blockage ratios between 1 and 10% were applied using the short-form equation by Thorn (1943) with a body shape value (K) of 0.96. A circular plate in the platform allowed yaw angle variation with five crosswind yaw angles investigated (−10°, 5°, 10°, 15°, 20°), in addition to the 0° experiment.

A six-axis Delta model force transducer (ATI, 2018) was attached to the hand-cycle model vertically in line with the model's centre of gravity (Fig. 2b). The error range was ±1.24 N at a 95% confidence interval. The error range was calculated from the calibration targets; 0.75% of the full-scale load. Force data were sampled for 180 s at a rate of 10 Hz after a 30 s settling period. Air temperature measurements inside the test chamber were used to correct force measurements to an air density at 15 °C and 101325 Pa, ensuring consistency across all experimental data and CFD simulation results. Local meteorological data was used to correct for the atmospheric pressure at the date of the experiments. A pitot tube was used to measure the stream-wise air velocity, to correct the force measurements to the desired 60 m/s velocity, for all the yaw angles tested. Previous experiments for quarter-scale cyclist models in the same wind-tunnel reported an approach-flow turbulence intensity below 0.2% (Blocken et al., 2016).

3. CFD simulations

3.1. Computational domain and boundary conditions

For the CFD validation, the simulations were performed with the same geometrical model as in the wind-tunnel experiments but in full scale, including all hand-cycle wheel supports, baseplate and platform surface in the CFD domain (Fig. 3). The platform was included as a no-slip wall. This allowed for boundary layer development on the platform as in the wind-tunnel experiments. A no-slip wall boundary condition with zero roughness was applied to the hand-cycle, supports, baseplate and platform surfaces. A cylindrical interface was used to rotate the hand-cycle geometry to the selected yaw angles. The computational domain and boundary conditions are shown in Fig. 3. The max blockage ratio for the domain at 20° was below the 3% maximum recommended (Blocken, 2015; Franke et al., 2010; Tominaga et al., 2008). A velocity of 15 m/s was imposed for all the yaw angles tested. Viscosity was 1.789×10^{-5} kg/ms and density was $1.225\,\mathrm{kg/m}^3$. After the validation study, the wheel supports, baseplate and platform surface were removed from the CFD domain for more accurate predictions of hand-cycling aerodynamics, see section 4.2.

3.2. Solver settings

The commercial CFD code ANSYS Fluent 16 (ANSYS Fluent, 2015) was used to solve the 3D Reynolds-averaged Navier–Stokes (RANS) equations using two turbulence models for closure: the 1-equation Spalart-Allmaras model (Spalart and Allmaras, 1992) and the 2-equation Shear Stress Transport (SST) k-ω model (Menter, 1994). The pseudo-transient implicit under-relaxation method was used with a time-step of 0.01 s, using the Coupled algorithm for pressure-velocity coupling, and the Least Squares Cell Based method to compute gradients. Aerodynamic forces were averaged at every pseudo-time-step over a period of 4000 steps. Second-order discretisation schemes were used throughout along with second-order pressure interpolation. The maximum values for the scaled residuals were: 1×10^{-5} for continuity, 1×10^{-7} for momentum, 1×10^{-4} for turbulent kinetic energy, 1×10^{-4} for specific dissipation rate and 1×10^{-6} for turbulent eddy viscosity where the Spalart-Allmaras turbulence model was used.

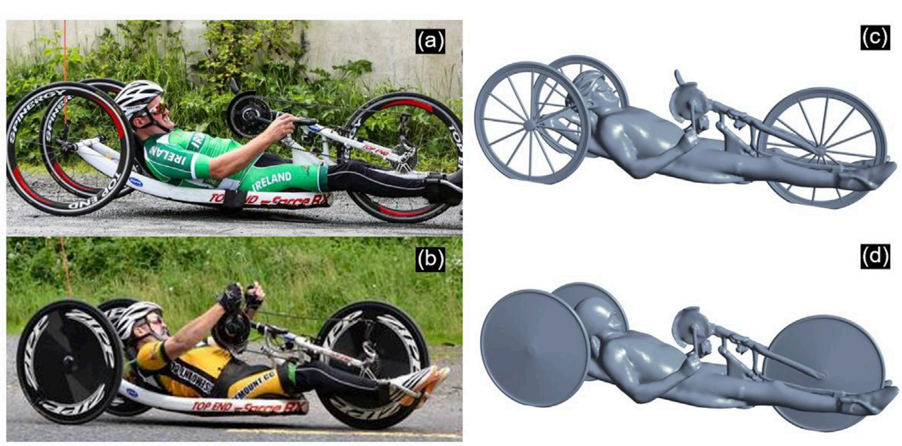

Fig. 1. Photos of an Irish H3 category hand-cyclist with spoked wheels for a road race, and (b) disk wheels for a TT event. (Photos copyright of Sportfile, Cycling Ireland and Paralympics Ireland, reproduced with permission). Part (c) and (d) illustrate the geometries used for this study to represent (a) and (b) respectively.