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A comparison of the wake structures of scale and full-scale pedalling cycling models

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Abstract

This paper presents a novel approach to better understand the unsteady aerodynamics associated with a dynamically pedalling cyclist. Using high resolution Particle Image Velocimetry (PIV) in a water channel, the large-scale wake structure is analysed for various phases of the crank cycle of a 1:4.5 scale-model cyclist/bicycle under both static and pedalling conditions. Both quasi-steady and dynamic pedalling leg results are compared with detailed velocity field surveys made in the wake of a full-scale pedalling cyclist mannequin of similar geometry and position in a wind tunnel. A time-averaged and phase-averaged analysis of the various flow regimes that occur throughout the pedal stroke shows good agreement between scale-model and full-scale mannequin investigations. This highlights the robustness of the formation of the primary wake flow structures when subjected to varying Reynolds number, bicycle/rider geometry and quasi-steady/dynamic pedalling conditions.

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Keywords: Aerodynamics; bluff-body; sports; cycling; wake structure; vortex flows.

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1. Introduction

Optimising aerodynamics is one of the most effective ways to gain a significant competitive advantage and performance gains in elite cycling. This is why leading nations and teams allocate significant resources to improving the aerodynamics of their athletes. Central to elite level cycling performance is the role that aerodynamic drag has on the speed and power requirements of cyclists. The aerodynamic drag component has been shown to account for up to 90% of the total resistive forces acting on cyclists travelling on relatively flat surfaces for speeds > 8.9 m/s [1]. This coupled with the fact that the power required to overcome aerodynamic drag 'P_{Aero}' varies with the freestream velocity cubed means that the overwhelming majority of the power output by cyclists at racing speeds goes into overcoming aerodynamic resistance [2].

Cyclists competing in individual cycling events have two options for reducing aerodynamic drag. Riders can minimise their projected frontal area 'A' and/or reduce their drag coefficient 'C_D'. Rider position has been shown to

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have the largest influence on these variables, followed by equipment selection and design [1,3,4]. As the frontal area and drag coefficient is influenced simultaneously when optimising position and equipment, predicting aerodynamic drag is often difficult due to the highly non-linear relationship between A and C_D. Through a better understanding of the three dimensional flows around cyclists and the primary fluid mechanisms having the largest influence on drag, informed decisions and potentially new optimal methods for reducing drag can be sought.

Recent advances in our understanding of flows around cyclists have come from improved experimental and numerical techniques. With advances in computer-aided-design (CAD) and manufacturing methods such as 3D-printing and CNC-machining, high resolution and detailed models can be produced from scanned data and 3D computer modelling. These numerical models of the rider/bicycle geometry can then in-turn be used as an input into computational fluid dynamic simulations (CFD). Numerical studies by Griffith *et al.* [5,6] and Defraeye *et al.* [7,8] have shown that such methods provide an effective additional tool for optimising and investigating cycling aerodynamics when run in parallel with an experimental program.

Experimental and numerical studies by Crouch *et al.* [9] and Griffith *et al.* [5] have shed light onto the dominant fluid mechanisms influence cycling aerodynamics by characterising the large-scale flow structures that develop in the wake. Wind tunnel investigations of Crouch *et al.* mapped the time-averaged flow in the wake of a full-scale mannequin for various static leg positions around a full 360° revolution of the crank. Large changes in the flow structure and aerodynamic drag, which varied up to 20%, was measured around the crank cycle. The major flow structure variants were characterised into symmetrical and asymmetrical flow regimes and were associated with low and high drag states. A low drag symmetrical flow regime corresponded to crank angles near to horizontal that resulted in the alignment of the upper thighs of both legs. The high drag asymmetrical state was found for crank angles where one leg was in a raised and the other in an extended position. For these phases of the crank cycle, a strong streamwise counter-rotating vortex pair that originates from the hip region of the mannequin was the primary wake feature. These findings were compared with investigations of the flow around a numerical model of the mannequin by Griffith *et al.* who found a good match in the downstream wake structure.

More recently investigations by Crouch *et al.* [10] have extended the quasi-steady understanding of the wake by investigating the large-scale wake structure under dynamic pedalling leg conditions. Phase-averaged velocity field measurements with a full-scale mannequin showed (for realistic racing cadences) the primary symmetric and asymmetric wake features were consistent for both the quasi-steady and dynamic leg results. This investigation continues to build upon our understanding of the three dimensional flow around the complete bicycle-rider system for dynamic leg conditions. This is achieved using a novel technique which incorporates a moving leg scale-model produced using 3D printing methods for highly resolved velocity field measurements obtained using PIV in a water channel.

2. Experimental Method

Figure 1 (a) shows the full-scale wind tunnel mannequin and the 1:4.5 scale water channel model. The models are both depicted in the 15° leg position which is defined as the crank angle 'θ'. The zero degree leg position corresponds to when the cranks are horizontally aligned with the left leg in a downstream location. The plastic scale-model rider and bicycle frame was manufactured using a Stratasys Object Connex 500 3D printer. The highest print resolution setting was used (print layers of $30\mu m$) and a conservative estimate puts the printing tolerance at 0.2 mm. Although minor design changes have been made to the scale-model, the major geometric features and dimensions have been scaled directly from the full-scale CAD wind tunnel mannequin geometry, detailed in Crouch *et al.* [9]. Alterations to the scale-model geometry have been made to allow for the rotation of the legs, 'smooth' surface transitions between intersecting limbs and ease of replacing body-parts. Features such as the head and helmet have been scaled directly from high resolution scanned data.

The major difference between the 1:4.5 scale and full-scale model is the bicycle frame and wheel geometry. The bike frame used in the wind tunnel studies is now outdated and was first released over 10 years ago. The simplified scale-model bicycle is based on the geometry of current Time-Trial (TT) bicycles from leading manufacturers. The major dimensions and cross-section characteristics of the frame members non-dimensionalised by the wheel base WB (229 mm) are detailed in table 1. In addition to the bicycle frame the wheels have been modelled as flat disks instead of open spoke wheels.