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An analysis of the wake of pedalling cyclists in a tandem formation

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Abstract

Aerodynamics is a critical factor in the performance of cyclists, with drag being the dominant resistive force at racing speeds. Many cycling events involve athletes riding in close proximity. Previous studies have shown that flow interactions result in significant drag reductions for tandem cyclists, inline parallel to the flow [1-5]. However, the flow mechanisms associated with these changes have not been well characterised to date.

This paper reports the results of wake surveys of an athlete in single and tandem formations in the Monash Wind Tunnel. Flow measurements were phase averaged over segments of the crank cycle to investigate the dynamic evolution of the wake of a pedalling cyclist. Results show that the dominant hip vortices previously identified in the wake of a single cyclist remain dominant in the trailing cyclist wake, with minimal reduction in vorticity. Wake profiles indicate the large drag saving experienced by a trailing cyclist are not due to disruption of the wake vortices or significant streamwise momentum recovery.

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1. Introduction

Aerodynamic resistance is a critical factor in the performance of cyclists. At racing speeds, drag is the dominant resistive force acting on a cyclist [6, 7]. For this reason, much interest has been placed in reducing the drag of a cyclist. Recent studies have shown that the wake of a cyclist is a complex topology that varies with the position of the legs [8, 9]. The cyclist wake is dominated by a pair of counter-rotating vortices that are formed from the hips of the cyclist. As the legs move around the crank cycle, the flow field changes the formation of these vortices. Crouch et al. [9] identified two characteristic flow regimes in the wake. A symmetric wake was observed when the thighs of the cyclist were level. This regime was characterized by low vorticity in the wake and weak coherent structures. It also corresponded to a minimum in drag. Conversely, a highly asymmetric flow regime was identified when the upper legs of the cyclist were at different levels. Stronger flow structures were found when one leg was raised with the hip angle at a minimum. This regime is characterized by a vortex separating high from the open hip and an opposite vortex separating low and close to the centreline behind the closed hip. These flow regimes were characterized in the wake of a static cyclist at a fixed leg position. Further work by Crouch et al. [10] confirmed that these dominant flow structures evolve at sufficient rate to still be present in the wake of a pedalling cyclist.

Many cycling events are mass start and involve athletes riding in close proximity to one another. The drag of an individual cyclist in a group is strongly influenced by the presence of other riders, with interaction effects being a function of spatial separation and athlete dimensions [1-5]. For two riders in tandem formation (one trailing the other) there is a significant drag for both the lead and trailing cyclists. Drag reduction for the leading rider has been reported of the order of 5% and the trailing rider as high as 49% [3]. Whilst the drag reduction for the trailing cyclist has been measured by several authors and widely acknowledged anecdotally, the changes to the cyclist flow field responsible for this reduction have received little focus. Barry et al. [11] showed that the

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dominant hip vortices observed in the wake of a single cyclist in isolation remain the primary features in the trailing cyclist wake. However, this work was conducted using static scale models.

To fully understand the flow field of cyclists in formation it is necessary to understand the flow behaviour at full scale Reynolds numbers for pedalling cyclists. This will provide a detailed and realistic insight into the nature of the wake of a trailing cyclist and identify any differences from that observed for a single cyclist.

2. Methodology

Experiments were conducted at full-scale in the Monash University three-quarter open jet wind tunnel using an athlete and a mannequin. Measurements of the flow velocity were taken first in the wake of a single cyclist to provide a reference condition. Flow data was then captured in the wake of the trailing rider in a tandem formation.

Cyclists were mounted on a cycling specific mounting rig with an elevated ground plane and splitter plate to minimize the boundary layer height. Each bicycle was held in place by a pair of struts fixing at the rear axle. An experienced elite level athlete was used as the primary cyclist for tests. The same athlete was used in the single rider tests and the trailing position in the tandem tests to provide direct comparison of the wakes. For all tests the athlete was mounted to the same location on the rig. In the two rider tandem tests a static mannequin was positioned ahead of the athlete, such that the athlete and measurement locations in the tunnel were constant. The mannequin was positioned with upper legs level, at a crank angle of 15^0 above the horizontal for the left leg. It has been shown that the dominant vortices in the wake of a trailing cyclist are not significantly affected by changes to the leading rider leg position for static cyclists [11].

Fig. 1 – (a) Mannequin and athlete in tandem formation showing pressure probe and traverse in wake. (b) Interrogation window behind athlete.

A multi-hole pressure probe (TFI Cobra) was used to record velocity measurements in the wake. This device resolves the three components of velocity from pressure at the offset faces on the probe head. The cobra probe is able to capture velocity data within a $\pm 45^0$ cone of acceptance and has a velocity resolution of 0.1 m/s. Data was sampled for 30 sec at 1000 Hz at each measurement location in the wake. An automated 2-axis traverse was used to position the probe and data recorded in a regularly spaced grid at 80 mm intervals. Higher resolution velocity field data from particle image velocimetry showed that this grid size provided sufficient resolution to identify large scale flow structures. However, small scale structures may be lost. Figure 1b shows the wake capture region, which extended from 700 mm above ground to a height of 1660 mm and 400 mm either side of the cyclist centreline. This region was chosen because the dominant vortices in a cyclist wake have been shown to form at the hips [8, 9].

As testing was conducted using a human it was necessary to utilize a coarse sampling grid to minimize the total sample time required for each wake survey. A limitation of athlete testing is that fatigue must be factored into the test program. Because the wake surveys are taken from point measurements, it was important that the athlete could hold, and recreate, the same posture on the bicycle for each sample over the course of the experiment. This was achieved by optimizing the resolution of the sample grid to minimize fatigue and monitoring rider position using a camera.

A magnetic sensor was mounted to the crank to identify the beginning of each pedal cycle. Each cycle was then synchronized and the wake data phase averaged over 12 discreet angular segments of the crank cycle to capture the dynamic evolution of the wake. For phase averaging the crank cycle was modelled with constant angular velocity so that each segment was of equal duration. Kitawaki & Oka [12] showed that the crank velocity is a function of crank angle. For an expert cyclist at a cadence of 100 RPM, the variation in angular velocity was found to be typically 2% from the mean crank velocity. For the current analysis, this equates to a maximum error of the order of 2^0 in crank angle position. Given the large size of the phase segments and the associated error with the leg position (± 1^0), it was considered reasonable to segment the crank cycle assuming a constant angular velocity. This is supported by evidence that the flow regimes have not been found to change on such rapid scales [9]. The crank position was referenced from the left crank horizontal and rearward being 0^0; imposing a unit circle origin at the bottom bracket.

3. Results

3.1 Time-Averaged Wake

Using the full data sample, a time-averaged view of the dynamic wake was analysed. Figure 2 shows the time-averaged streamwise velocity profiles of the single rider and tandem formation. Wake profiles were generated by linearly interpolating between the sample points. The single rider result shows that the time averaged wake of a cyclist is symmetric. Given the periodic nature of the leg motion when pedalling, this result is expected. The tandem wake is also symmetric below the legs, however, an asymmetry is observed around hip height (z = 1.2 m), possibly associated with a bias in the position of the human rider. Given that the effect is more pronounced in the trailing rider result than the single rider case, it suggests that when the rider is in the wake of the leader the asymmetry is magnified. The maximum difference in the left and right sides is only 5% of the freestream value. Taking the integral average over the upper wake region shows minimal difference between the single and tandem cases. The greatest difference between the two occurs in the lower portion of the wake region (below z = 1.0 m) with a greater deficit evident in the tandem wake profile. This asymmetry was found to only be prominent in the streamwise component of velocity.

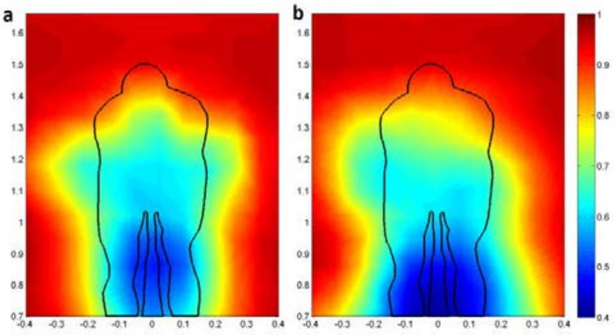

Fig. 2 - Time averaged normalised streamwise velocity in the wake of (a) a single pedalling cyclist (human), (b) a tandem pair with dynamic athlete (human) in trailing position

Drag was measured on the athlete during both wake surveys and showed a 40% drag reduction when in the trailing position of the tandem formation. This is consistent with literature [3]. Mean streamwise velocity over the interrogation was found to be 0.82 and 0.78 for the single and tandem wakes respectively. The reduction in streamwise velocity for the tandem wake will be contributed by a reduction in the pressure acting on the front of the trailing rider as it encounters the low energy wake of the lead rider and is not indicative of total energy loss over the trailing rider. However, this does show that there is not significant streamwise energy recovery in the tandem wake contributing to the drag reduction. Despite the low pressure that will act on the face of the trailing rider, it is of interest to understand how the flow structures in the trailing rider wake prevail.

3.2 Vorticity

Flow measurements from the wake of single and tandem cyclists were phase averaged over 12 equal duration segments of the crank cycle. From these velocity fields the dynamic changes occurring in the wake of a pedalling cyclist were identified. Vorticity was computed from the phase averaged velocity fields to show the dominant hip vortices previously observed in the wakes of static cyclists; where vorticity is defined as the curl of the cross-section plane velocity field. Figures 3 and 4 show the phase averaged streamwise vorticity for the single and tandem wakes respectively.

The dominant streamwise vortices that form from the cyclist's hips are clearly evident in the centre of each profile. For the majority of the crank cycle, the upper legs are not level, thus the characteristic asymmetric profile is evident across the majority of profiles. It was previously described by Crouch et al. [9] that when a leg is raised and closes off the hip angle the flow wraps over that hip and the rear of the rider and the resulting hip vortex occurs lower in the wake. By contrast, the open hip results in higher separation and the resulting vortex is seen to sit higher in the wake. This was also seen for scale model cyclists [11]. However, it is noted that the sign of the vortices from each hip is constant around the crank cycle. It is only the positions of the vortices that change. This behaviour, previously observed for the static cases, is also evident in the phase averaged dynamic profiles.

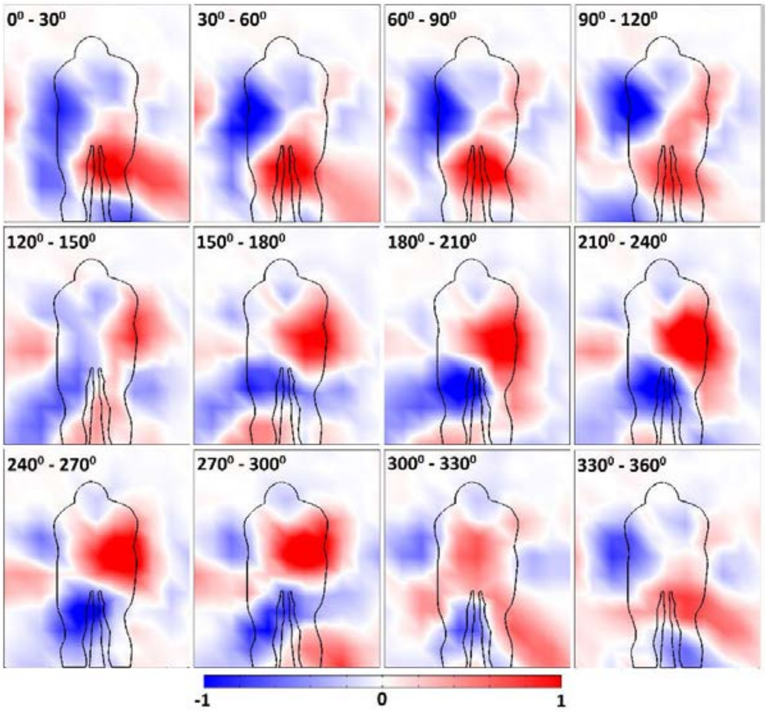

Fig. 3 - Streamwise vorticity in the wake of a single pedalling cyclist, phase averaged over 30^0 segments of the crank cycle

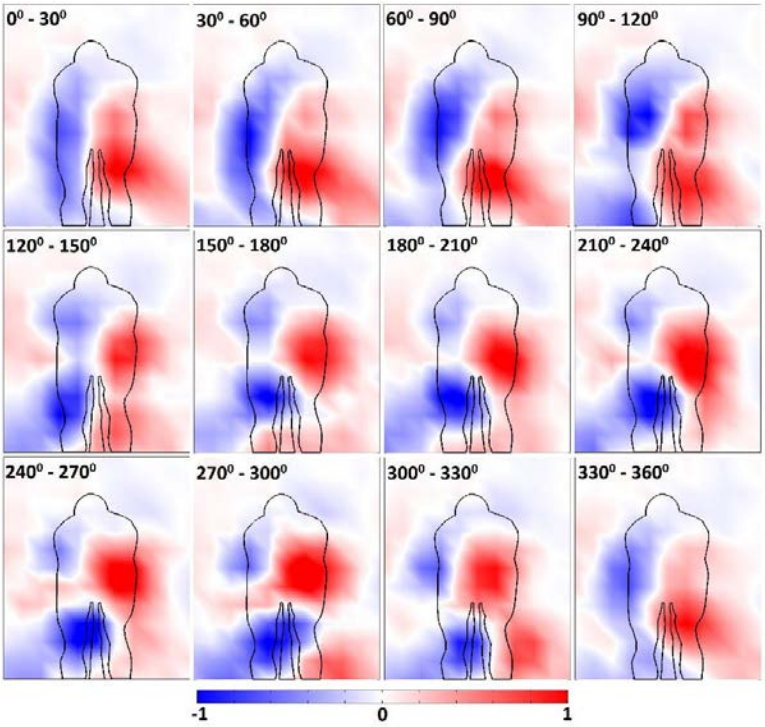

Fig. 4- Streamwise vorticity in the wake of a trailing pedalling cyclist in a tandem formation, phase averaged over 30^0 segments of the crank cycle

For crank angles of $0^0 – 120^0$ for both cases (Figures 3 &4) the negative left hip vortex is seen to sit up higher in the wake, with the positive right hip vortex sitting lower. As the legs move around the crank cycle a transition point occurs where the profile shape reverses and the positions of the left and right hip vortices switch. This can be seen to occur between 90^0 and 150^0. Beyond this point the right positive vortex sits higher than the negative left vortex. This result confirms that the primary hip vortices identified in static wake profiles persist in the wake of dynamic cyclist. Due to the spatial resolution of measurements it is not possible to identify the smaller scale structures previously seen in static profiles. However, the primary hip vortices, which are the dominant feature in the cyclist wake, are distinguishable in the dynamic wake of a pedalling athlete.

Comparing the single and tandem rider cases, the same periodic behaviour is observed in both sets of profiles. Furthermore, the streamwise vorticity is not significantly lower in the tandem wake when compared to the single rider case. This shows that the formation of the hip vortices over a rider in a tandem formation is not significantly disrupted by the presence of the upstream rider. The persistent presence of these primary vortices in the tandem cyclist wake suggests that the large drag reduction observed for a trailing rider is not due to disruption of dominant wake structures. It is also noted that the magnitude of vorticity observed in the dynamic wake is reduced compared to previous static results. This suggests that the dynamic evolution does weaken the formation and sustained vorticity of the hip vortices.

3.3 Convection Velocity

The vorticity profiles show that the wake profile at $0^0 – 30^0$ crank angles do not coincide with the symmetric flow regime previously identified in static tests. Similarly for the second transition point at 195^0. The reason for this is that the wake profiles are indexed to the current position of the cranks. As the wake is being measured downstream of the athlete there is convection time for the flow to travel downstream from the athlete to the point of measurement. During this time the cranks continue to rotate. As a result, the crank angle index applied to the phase averaged results does not line up with the static leg position at which that regime would be expected. This creates an effective phase shift between the wake profiles of the dynamic cyclist and those seen for a cyclist at a static leg position.

The phase shift in the results can be estimated by modelling a wake convection velocity. Given the velocity gradients across the wake, different regions of the wake will convect at different rates. And as structures in the wake change around the crank angle, velocity in the wake at a given location will not be a constant. As an approximation, a mean wake velocity was determined and used to model the convection velocity [13]. This was calculated from the time averaged mean velocity results for the single and tandem cases respectively. To exclude the freestream conditions at the edges of the interrogation region the flow was averaged over a window which closely enclosed the athlete dimensions; 400mm wide, based on the athletes shoulder width, and up to a height of 1500mm, the top of the athlete’s helmet. Within this region the mean normalised streamwise velocity was calculated to be 0.75 and 0.70 for the single and tandem cases respectively. These values were then used to model a wake convection velocity. A convection length of 750 mm was used as the distance from the hips to the measurement plane. Given an average cadence of 95.5 RPM and 92.7 RPM it was possible to determine a phase shift of 31^0 and 32^0 for the single and tandem wakes, respectively.

A visual comparison of the profiles suggests that that the phase shift is actually far greater than the calculated values of 31^0 and 32^0. By inspection, the transition region is first evident at the $90^0 – 120^0$ segment. The transition region corresponds to the point where the cyclist’s upper legs are passing through the level position as the profiles appear to become less biased in their asymmetries as the legs approach the symmetry condition before switching. For this athlete, the thighs parallel positon occurred at 23^0 crank angle. This results in an approximate phase shift of the order of 67^0, if the transition point is taken as 90^0 from the profiles in Figure 3 & 4. This equates to a convection velocity of 0.34, which is below the minimum velocity measured in the wake. Despite the limitations of this technique, it can be concluded that there is some additional mechanism associated with the generation and transport of the dominant wake structures in the wake of a cyclist causing the effective lag. This appears to be linked to the process of evolution of the wake structures and formation from a moving leg differing to that observed from the time averaged wake of a static cyclist at a fixed leg position. Comparing the single and tandem cases, it can also be seen that the offset is of similar order. Given that the tandem wake has a slightly lower mean velocity, it is expected that the phase offset will be slightly greater than the single case. However, this will be small given that the difference in mean velocity is of the order of a few percent. In the context of these results it is not possible to resolve differences of that scale. It is, therefore, reasonable to model phase shift on the same order for the single and tandem wakes in this case, as is evident from the profiles, which show the two data sets to be aligned.

4. Conclusion

The dynamic wake of a pedalling cyclist was investigated by conducting wake surveys behind a single cyclist and a two rider tandem formation. Time-averaged streamwise velocity profiles showed a greater mean deficit in the tandem wake compared to that of a single rider. This indicates that the drag reduction for a trailing cyclist is due to encountering lower energy flow, and not a result of streamwise momentum recovery in the trailing rider wake. Synchronizing flow measurements with the crank cycle meant that the time varying wake could be phase averaged into discreet crank segments to investigate the dynamic evolution of the wake flow. Profiles of streamwise vorticity in the wake of a cyclist show that the dominant hip vortices identified in static profiles are evident in the wake of a pedalling cyclist. Transition between the two asymmetric wake regimes are observable in both the single rider and tandem wake profiles. This shows consistency with previously published results from tests with static cyclists. The tandem wake does not exhibit significant reduction in vorticity compared to the single rider wake. This indicates that the large drag saving experienced by a trailing cyclist is not the result of disruption to the primary wake structures.

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