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Flow interactions between two inline cyclists

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Abstract

Cyclists travelling in close proximity are subject to aerodynamic flow interactions. This has been observed in force results with significant drag reductions observed; particularly for the trailing rider. However, the flow mechanisms responsible have not previously been investigated. Particle Image Velocimetry was conducted on two scale model cyclists in a tandem formation in a water channel. Velocity fields showed that the wake of a trailing rider does not differ significantly from that of a single cyclist. The primary flow change was observed upstream of the trailing rider where the wake of the leader significantly decreases the streamwise velocity. This lower energy at the inflow condition for the trailing rider is the main mechanism responsible for the large drag reductions.

Introduction

Aerodynamics is of great importance to road and track cycling because it is the dominant form of resistance that the athlete must overcome. At elite racing speeds over 90% of total resistance is aerodynamic drag [10]. The ability to reduce drag therefore has the potential to significantly improve performance. This has driven a significant amount of research into the optimisation of single rider aerodynamics. However, understanding the interactions between cyclists is less well understood. This is despite the majority of road races being mass start events, in addition to specific team events on both the road and track. It has been known anecdotally for over a century that drafting offers significant benefits to cyclists, but the mechanisms behind the phenomenon are still not well understood.

Several authors have previously characterised interactions between two tandem cyclists in terms of changing drag force [1-3,5,9,15]. All have shown that drag is a function of spatial position with drag of the trailing rider increasing with both axial separation and lateral displacement. At minimum distance from the lead rider and aligned laterally drag reduction for the trailing rider has been reported in the range of 29-49% for experimental studies [1,3,9,15]. With a bicycle length gap between the lead and trail this drag saving is reduced to 10-30%. A saving of up to 5% has also been reported for the lead rider.

To date, little work has been conducted to understand the flow field changes that cause these drag savings. Computational simulations of two riders [2,5] reported an increase in base pressure for the lead rider in a tandem pair. This will contribute to the drag reduction for the lead rider but does not explain the much greater drag reduction for the trailing rider.

By contrast, there is a large body of knowledge accumulated for flow around cylinders. For two semi-infinite cylinders several studies have identified that there are two flow regimes with a transition at a separation distance of 3.5 diameters [7,8,13,14]. However, these two distinct flow regimes were observed at Reynolds numbers, below 4.5×10^5. For higher Reynolds numbers, such as for a cyclist, it has been shown that this discontinuity is no longer evident [6,11]. They also found that the trailing cylinder drag is less sensitive to separation distance. Beyond 2.8 diameters the downstream cylinder was found to be primarily influenced by sheltering effects from the lead due to the reduced incoming velocity and high turbulence intensity ahead of the trailing body.

Ground vehicles share similarities with cycling with ground plane proximity and three dimensional effects. However, flow characterisations have been limited to simplified geometries (Ahmed bodies). It has been shown that surface pressure on the rear of the trailing Ahmed body in a tandem pair matches that of the isolated single body [12].

Whilst the flow field between multiple cyclists is not well understood, recent work by Crouch et al. [4] has provided new insight into the flow field around a single cyclist. They have shown that the wake of a cyclist is dominated by counter-rotating vortex pairs that vary with leg position. Furthermore, the drag of the cyclist also varies with leg position. It was also determined that the majority of a cyclist wake is attributed to these wake structures. Two primary flow regimes were identified corresponding to the position of the rider thighs. With upper legs level the flow regime is symmetric and corresponds to minimum drag. With one leg raised the flow regime is highly asymmetric and this corresponds to the maximum drag case. These were defined by left crank arm above horizontal from rearward with the symmetric regime occurring at 15^0 and the asymmetric case at 75^0.

Significant aerodynamic interactions have been observed for multiple cyclists travelling in close proximity through measurement of drag forces. However, the flow mechanisms responsible have not yet been identified. A greater understanding of these effects has the potential to deliver significant performance benefits for athletes as well as commuters. Starting from our new understanding of the flow field of a single cyclist, the wake of a tandem pair has been examined to determine the influence of aerodynamic interactions.

Methodology

Two identical scale model cyclists were constructed for use in flow experiments in the Monash University FLAIR water channel. Models were 1:7 scale and were rapid prototyped to ensure geometric similarity. The geometry is a replication of the Monash anthropomorphic cycling mannequin, which was designed from real athlete dimensions. Both cyclists were positioned at a crank angle of 15^0, defined from the left crank rearward and above horizontal. This was identified as the minimum drag case and generated a symmetric wake structure [4]. This position was selected because the symmetrical wake is expected to most closely represent the time averaged wake of a dynamic pedalling cyclist. Bicycles were modelled using simplified frames with round tubes, no handlebars and flat disks as wheels. As key flow structures are generated by the athlete's geometry and this contributes the majority of the drag, a simplified geometry bicycle was considered sufficient. Two pairs of struts at the rear axle and single at the front held the models in place. The water channel has channel dimensions of 0.6m wide, 0.8m deep and a test section length of 4m. Its free-stream turbulence level is less than 1%. Models were mounted upside down with an artificial ground plane suspended in the centre of channel. The ground plane controls the oncoming upstream flow condition and eliminates any free-surface effects on the flow field.

Particle Image Velocimetry was used to obtain velocity components in the flow cross sections. A single camera setup allowed for two-dimensional data. Taking cross sections in the wake of the cyclists obtained vertical and spanwise velocity components. No streamwise velocity data can be collected from this plane. Images were captured at three planes downstream of the trailing rider; at quarter chord, half chord and a chord length downstream of the rear of the rider. The chord length was defined as the length of the athlete's torso. This was also used as the characteristic length for defining the Reynolds number, which was 33,000 for these tests.

Single rider results were first collected to provide a reference condition and for comparison against established literature for a full scale cyclist. Cyclists were tested in a tandem formation; aligned parallel to the flow direction. To test the effect of separation distance two configurations were tested. Firstly with the trailing rider at minimum practical distance behind the leader; this equates to approximately 150mm at full scale. The second was with a full bicycle length between the two cyclists.

Results

Technique Validation – Comparison with Full Scale

The Reynolds number of the cyclists in the water channel was 33,000. This is approximately a factor of 15 lower than the Reynolds number of a cyclist travelling at 50km/h. This was limited by the maximum flow rate of the channel.

Full scale investigations have previously been conducted at Monash University using real cyclists and full scale mannequins in the wind tunnel, where realistic Reynolds numbers can be achieved [4]. However, the facility at Monash does not currently allow for detailed non-intrusive flow mapping such as PIV. The use of scale models in the water channel allows for high resolution full field flow measurements. The reduction in Reynolds number achievable with scale models is a clear limitation of this method but is seen as a compromise in pursuit of greater understanding of the flow field interactions between cyclists.

To ensure that the scale results were able to replicate the full scale flow field a comparison was conducted against the full scale mannequin results of Crouch et al. [4]. Given the geometric similarity between the scale model of this study and the Monash anthropomorphic cycling mannequin, it is expected that the scale geometry at full scale Reynolds number would have a matching flow field. Therefore, flow changes in this comparison will be the result of Reynolds effects only; not geometric nuances. Figure 1 shows the streamwise vorticity results in the wake of a full scale mannequin at a half chord length downstream (left) and full chord length (right). Figure 2 shows the vorticity results from the scale model tests with planes at quarter, half and full chord length downstream, respectively. For comparison, these results are cropped and scaled to have the same contour gradient as that of Crouch et al. [4]. Both results are for a cyclist with legs positioned at a crank angle of 15^0 (left crank rearward, above horizontal).

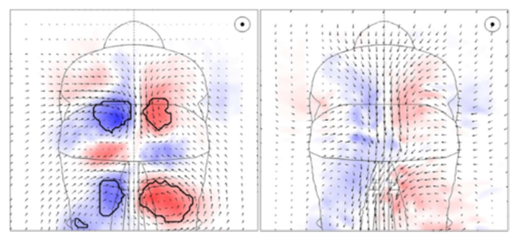

Fig 1. Streamwise vorticity (s^{-1}) in the wake of a full scale cyclist at a crank angle of 15^0 and a Reynolds number of 6.9×10^5. Left; half chord, right; chord length downstream of the rear of the rider [4].

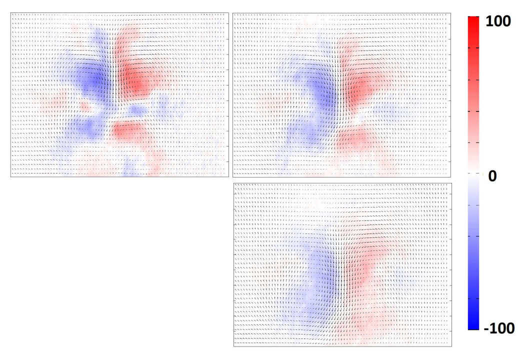

Fig 2. Streamwise vorticity (s^{-1}) in the wake of 1:7 scale model cyclist in the water channel. Reynolds number of 3.3×10^4 and legs positioned at 15^0 crank angle. Clockwise from top left; quarter chord, half chord, full chord length downstream of the rear of the rider.

The symmetrical wake structure previously identified for this leg position at full scale was also observed in the scale model results. Both vorticity and velocity vectors are similar between the full scale and water channel sets of results. However, the clarity of the structures does differ. At a chord length downstream both sets of results show broad regions of vorticity, without specifically identifiable vortex pairs. At a half chord length at full scale, three pairs of structures become visible. By contrast, the scale results are less clearly defined. However, at the quarter chord plane for the scale results the three vortex pairs become apparent. Crouch et al. [4] did not collect data at a quarter chord plane. This result is not unexpected as the lower Reynolds number flow of the scale models will have greater viscous effects that will damp out the turbulent structures more rapidly. Velocity vectors from Crouch et al. [4] are from point measurements whereas vectors from PIV are interpolations from a higher resolution surface.

This comparison shows that the scale model results exhibit the same primary wake structures as that of a full scale cyclist, despite the lower Reynolds number. The primary point of difference is an increased rate of decay in vorticity in the downstream direction. The strong degree of similarity in the primary wake structures behind the scale model shows that the flow field is comparable to that of full scale Reynolds number flow. This indicates that the formation of the primary wake structures is largely independent of Reynolds number in this range. Therefore, it is assumed that flow interactions observed for scale model cyclists will be representative of the flow field of real world cyclists. The faster vorticity dissipation suggests that interaction effects may be conservative as the potential impact of the leader wake on the trailing rider may be diminished.

<u>Wake of riders in a tandem pair</u>

Cross section velocity planes were captured in the wake behind the trailing rider in a two rider tandem formation; the riders were positioned inline and parallel to the flow. Two separation distances were tested to assess the influence of proximity on the interactions. Images were collected at quarter chord, half chord and a full chord length downstream of the trailing rider. Figure 3 shows contours of non-dimensional streamwise vorticity and in plane velocity vectors for the quarter chord plane of a single rider, tandem riders at minimum separation and tandem riders with bicycle length gap. Only the quarter chord results are presented as these show the highest intensity and detail of structures, allowing for a clearer comparison. Note that at quarter chord the plane slices through the rear wheel. This resulted in the localised very high intensity line on the centreline of the images.

With the trailing rider close to the leader (Figure 3b) the upper pair of structures are still clearly present, although peak vorticity is decreased. Below this the features are less distinct than in the single rider wake and there is some cross combining of regions across the centreline. Larger regions seen in the single rider result appear to have dispersed and combined with smaller regions in the lower part of the wake. Overall structure of the trailing rider wake remains similar to the single rider result but with generally decreased intensity. There is no significant disruption to the formation of the primary structures.

At a bicycle length downstream (Figure 3c) the wake of the trailing rider shows strong similarity with the single rider result; more so than at the smaller separation. Three stacked pairs of counter rotating vortices behind the torso are clearly evident. No combining of regions as seen for smaller separation between riders. A slight decrease in intensity is evident across the whole wake. Otherwise all structures maintain strong similarity with the single rider result.

At a greater distance downstream the wake is more similar to that of an isolated rider case. This was expected as proximity to the lead rider will cause the inflow conditions to contain stronger structures and be generally more turbulent. At a bicycle length downstream the wake from the lead rider has more time to degrade, allowing greater energy recovery from the freestream. This leads to inflow conditions for the trailing rider being closer to that of freestream compared to a rider travelling close behind the leader.

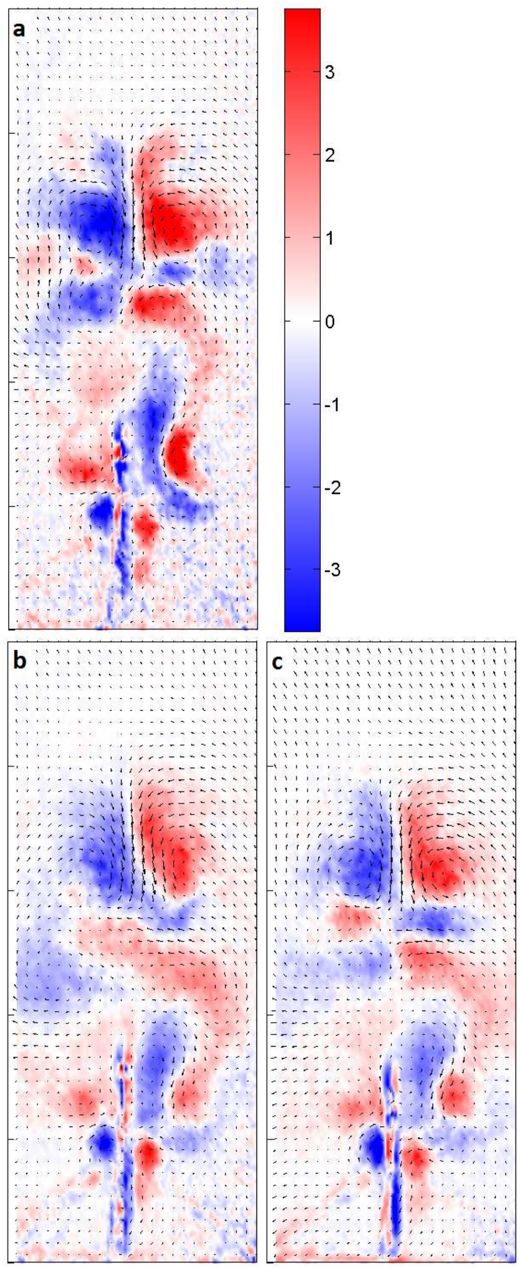

Figure 3. Streamwise vorticity (dimensionless) in the wake of a 1:7 scale cyclist at a quarter chord downstream of rider rear. Reynolds number of $3.3x10^4$ and legs positioned at 15^0 crank angle. Top (a); single rider, Bottom left (b); trailing rider at minimum separation, Bottom right (c); trailing rider at bicycle length behind leader.

Results are presented for 15^0 crank angle position only. Additional experiments (not shown here) on cyclists at the 75^0 crank angle confirm the same result. The wake of a trailing rider maintains the same dominant flow structures as seen for a single rider at the same leg position.

Conclusion

This paper has presented experimental velocity field data for cyclists travelling in a tandem formation. Velocity components were obtained from particle image velocimetry taken in the wake of scale models in a water channel. To the knowledge of the authors this is the first time that the wake flow of multiple riders has been presented.

Due to the lower Reynolds number achievable in the water channel it was necessary to conduct a validation study to ensure that the scale model flow provided similarity with full scale flow for real world cycling. Streamwise vorticity contours for a single rider were compared with the full scale results obtained in wind tunnels by Crouch et al. (2014). It was found that the wake of the scale model was similar in structure to that of the full scale cyclist despite the lower Reynolds number. The only key difference was an increased rate of dissipation in the vorticity; postulated as being the result of greater viscous effects.

Two tandem formations were then tested with the trailing rider at minimum distance behind the leader and with a bicycle length gap between them. These velocity fields were then compared to the result of a single rider. At minimum separation the flow still shows strong similarity with the single rider field; however there is some decrease in intensity across the wake. The primary vortex pairs are still clearly evident but there is some disruption to structures lower in the wake. With a bicycle length gap the flow structure exhibits negligible difference from the single rider flow, with only a slight decrease in intensity of vorticity. This is due to the structures from the lead rider dissipating before reaching the trailing rider as well as greater energy recovery from the freestream. This result confirms the work of Crouch et al. that the flow field around a cyclist is primarily a function of geometry. It also shows that even disrupted inflow conditions, such as travelling in the wake of another cyclist, does not significantly disrupt the wake structure.

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