17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

Aerodynamics of High Cadence Cycling

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Abstract

Cadence selection plays an important role in the performance of an individual cyclist, but it has been difficult to determine in general if a certain cadence is more aerodynamically advantageous than others. This paper investigates the effect of cadence on the aerodynamic drag of a cyclist whose leg morphology and profile during pedalling is known.

Introduction

In cycling, cadence is defined as the number of crank revolutions per minute (rpm). Generally in cycling, pedalling speed in excess of 100 rpm is considered as high cadence. Abbiss et al. [1] suggests that the biomechanical efficiency of a pedalling cyclist improves at high cadence. High cadence cycling at competitive speed requires immense power input and hence is usually only suitable for sprint events such as track cycling.

Track cycling events are generally held inside a closed velodrome. This allows the cycle to be operated at conditions that are close to condition for which it was optimised. Hence, pedalling at a predetermined optimum cadence could potentially improve the performance of the cyclist significantly.

Kyle et al. [2] estimates that at the top speed, the contribution of the aerodynamic drag to the total resistive force on the cyclist is over 90%. Hence, significant research has been attempted to reduce the drag experienced by the cyclist. However, according to Luke et al. [3], the majority of this research does not consider the unsteady flow caused by the moving legs. This paper sets out to redress this shortcoming and evaluate the effect of the unsteady flow behind the cyclist to the measured drag. The flow field behind the cyclist will be analysed in detail to characterise the complex three-dimensional flow features. This database will provide validation for a concurrent computation fluid dynamic study of unsteady aerodynamic associated with high cadence cycling.

Experiment

One of the main aims of this study is to accurately map the unsteady flow behind the cyclist. These experiments require collection of data at specified grid points. It was proposed to build up this data set by traversing a probe through the grid points serially and collecting data at each point for a specified number of crank cycles. Two hot-wire probes, offset from each other in span-wise direction were used to measure the stream-wise velocity component behind the cycling manikin. To ensure the consistency of leg geometry during sampling, it was proposed to design an autonomous manikin that maintained the desired cycling motion. Currently a drag balance is not used to obtain the drag measurement directly, but an estimate of the drag is calculated from momentum deficit of the measured flow field. The experiment setup used to obtain the velocity measurement is shown in figure 2.

Manikin

The dimensions of the manikin will affect the flow and hence the measured drag. Thus, it was decided to concentrate the study on a single athlete, whos leg geometry and joint profile during cycling were already determined and supplied by the Australian Institute of Sport (AIS).

Manikin production

The three dimensional geometry of an elite cyclist was obtained using a laser scanner by AIS. The topology mesh was cleaned up and segmented to smaller size which could be cut using a computer numerically controlled (CNC) machine. This allowed production of medium density grade polystyrene foam ‘flesh’ that closely matches the leg morphology of the elite cyclist. The CNC cut foam ‘flesh’ was then fitted to an aluminum skeleton which provides the necessary strength and rigidity of the manikin. An elastic foam was glued between the flesh in the knee and ankle region to provide the necessary movement during cycling. Finally the manikin was dressed in tights to contain all the components and provide a realistic aerodynamic surface. The resulting manikin is shown in figure 2.

Pedal Motion Modelling

The leg of a cyclist was modelled as a three degree of freedom body with revolute joints to represent the hip, knee and ankle. The proposed model ignored the joint in the ball of the foot where it was considered that the joint was immobile during the course of cycling due to high stiffness sole of a cycling shoe. This proposed model of the leg enforces planar alignment of all of its connecting elements (i.e. knee, hip and ankle all lie in the same plane). A schematic diagram of proposed manikin is shown in figure 1.

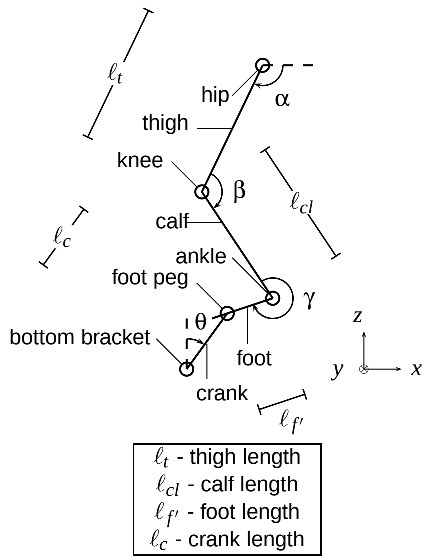


Figure 1: Schematic diagram of a leg of the manikin

The mapping from crank angle θ to hip angle α was approxi-

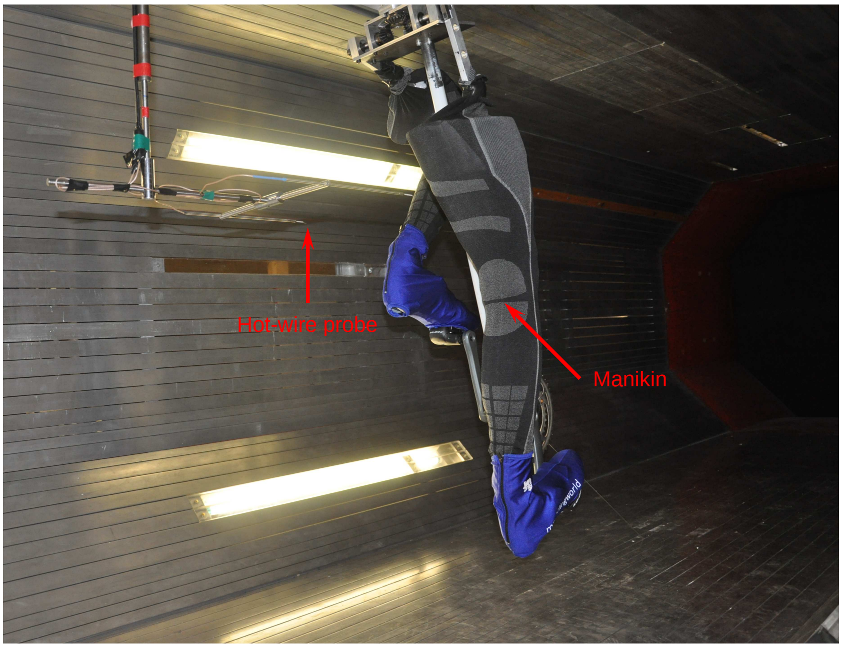


Figure 2: The experiment setup

mated with a sinusoidal function of form

$$\alpha(\theta) = a\cos(\theta + b) + c \tag{1}$$

This approximation means that the leg of the manikin is constrained in one degree due to constant length of the crank. Hence, to fully define the leg of the manikin, two more degrees of constraint are required. Thus, it was proposed that the crank and the hip be driven by separate motors to enable full control of the cycling motion. By building a mapping from crank angle position θ to desired hip angle position α and enforcing it using the servo motor located at the hip, the desired manikin geometry can be maintained for each full revolution of the crank angle. With a crank motor providing constant crank rotation and a feedback loop to the hip servo motor enforcing the appropriate relationship between θ and α the manikin could be set up to follow the desired cycling motion profile. This constant, reliable and sustainable pedalling motion allows accurate construction of histories of velocity fluctuation at each grid point downstream of the manikin (by sampling at each grid point and using phase averaging techniques).

Constants a, b and c need to be chosen so that they provide the best fit function to the data set of the real hip, knee and ankle position of the elite cyclist as supplied by AIS. The sinusoidal nature of the mapping function from θ to α ensures that the hip angle of the first leg, α_1 and the hip angle of the second leg, α_2 are out of phase by π. Thus,

$$\alpha_2(\theta) - c = \alpha_1(\theta + \pi) - c \tag{2}$$

Placement of a motor at the hip and fulfilment of equation (2) by the hip angles of each leg means that both legs of the manikin can be fully constrained by use of a T gearbox between the hip motor and thighs of each leg. This setup also ensures that each leg maintains the mapping from the crank angle to the hip angle given by equation (1). Figure 3(*b*) shows a comparison of the position of hip, knee and ankle joints as measured for a real elite athlete by AIS and the values obtained from simulation of the proposed manikin setup. The suffix ‘AIS’ indicate pedalling motion of an elite cyclist taken by AIS and the suffix ‘pm’ indicate the proposed manikin motion. Figure 3(*a*) also shows comparison of the hip, the knee and the ankle joints angles. From figure 3 it can be concluded that the proposed manikin motion follows the motion of the real athlete very closely.

Analysis

It is a common approach to decompose velocity data in a turbulent fields to mean and fluctuating components and use them to describe the velocity fields. For periodic flows, this idea can be expanded to decomposing velocity data into phase averaged velocity and fluctuating components. Thus, the effect of the periodic turbulence to the flow field can be analysed using phased averaged data.

The decomposition into the the phase locked average and the fluctuating components for stream-wise velocity are given by

$$u = \langle u \rangle + u' \tag{3}$$

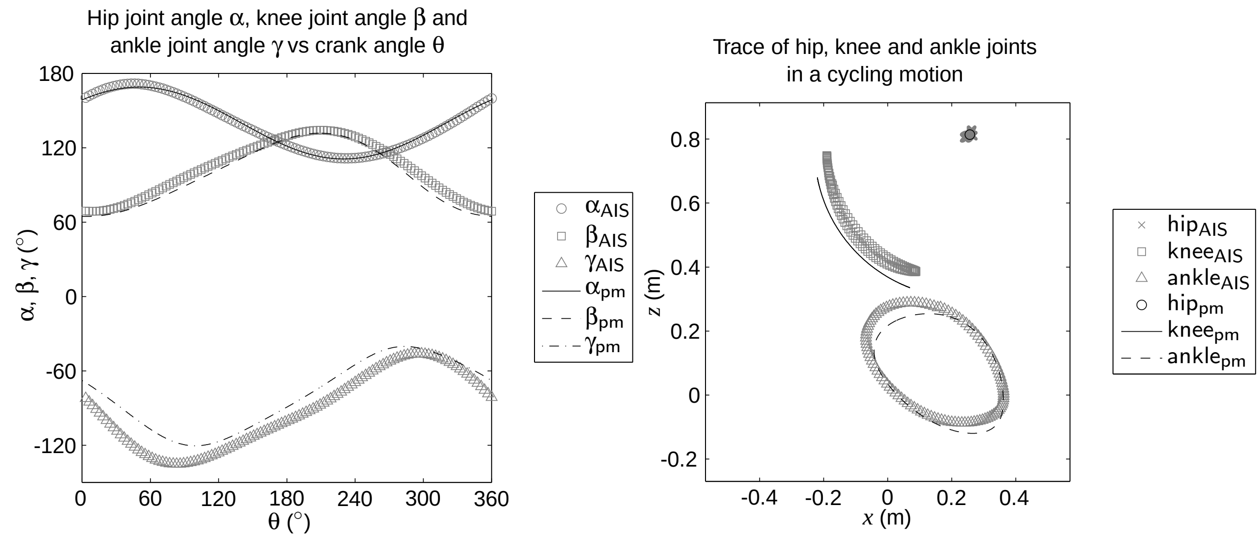
where,
u is the stream-wise velocity
$\langle u \rangle$ is the phase averaged stream-wise velocity component (which is a function of θ) and
u' is the fluctuating stream-wise velocity component

Periodic averaged and fluctuating stream-wise velocity normalised by the free-stream velocity U_∞ are given respectively by

$$\langle u_n \rangle = \langle u \rangle / U_\infty \quad ; \quad u'_n = u'/U_\infty \tag{4}$$

The drag on the object can be estimated by taking an integral of momentum change due to a velocity deficit in the far wake region. This is because, at sufficient downstream locations, far from a wake source, the majority of the momentum deficit is due to the velocity deficit (i.e. pressure terms and turbulent stresses are ignored). Thus, estimation of the phase-averaged drag coefficient of an object $\langle C_d^* \rangle$ can be calculated using

$$\langle C_d^* \rangle = \frac{2}{A} \int_0^A \langle u_n \rangle (1 - \langle u_n \rangle)\, dA \tag{5}$$



(a) (b)

Figure 3: Comparison of the proposed manikin motion and an actual pedalling motion of an elite cyclist

where,
$\langle u_n \rangle$ is the phase-averaged flow velocity in the stream-wise direction and A is the total area

Stream-wise turbulence intensity $\langle I_x \rangle$ can be calculated using

$$\langle I_x \rangle = \sqrt{\frac{1}{A}\int_0^A \langle u_n'^2 \rangle \, dA} \tag{6}$$

where,
$\langle u_n'^2 \rangle$ is the phase-averaged turbulent intensity in the stream-wise direction and A is the total area

Results

It is proposed that the free-stream velocity and the cadence can be scaled by a factor and still maintain the same flow features when the phase-averaging is performed. For a manikin that is the same size as the athlete, for correct scaling the factor U_∞/ω must be a constant between the experiment and the real situation (ω is cadence). Hence, the velocity measurement taken at the same stream-wise distance down-stream of the cycle should be equivalent once normalised by the free-stream velocity. This would allow the experiment to be conducted at lower cadence which would reduce the torque requirement of the hip motor and also reduce the tolerance in mapping between the crank and the hip motor.

It was decided that for a preliminary measurement a free-stream velocity of 4.9 ms^{-1} and a cadence of 30 rpm will be used. When the free-stream and the cadence are scaled appropriately, this matches a more realistic free-stream velocity of 19.6 ms^{-1} and a cadence of 120 rpm which is within a capable range of an elite cyclist. The velocity measurements were taken over a grid located on a plane that is 0.4m down-stream of the manikin (see figure 6).

The velocity measurements obtained were decomposed into the phase-averaged and the fluctuating components and normalised by the free-stream velocity. Figure 4 and 5 show the normalised phase-averaged and the normalised fluctuating velocity respectivelty at $\theta = 0°$ (Note a similar figure can be produced for any angle $0 < \theta < 2\pi$) .

The position of the manikin at $\theta = 0°$ and the plane $x = 0.4$m is shown in figure 6. Thus, a prominent low velocity and high turbulent region at negative span-wise direction is due to the extended right leg at the down-stroke. In this position, the left leg is retracted for the up-stroke and only the knee region seems to have a prominent low velocity and high turbulent region.

Estimates of the phase-averaged drag coefficient $\langle C_d^* \rangle$ and the stream-wise turbulent intensity $\langle I_t \rangle$ were calculated after decomposition using equation (5), (6) and are shown in figure 7. Both the drag coefficient and the turbulent intensity obtain their peak values when the crank is in the near vertical position. This is to be expected as the blockage due to the leg is highest when the crank is vertical.

Conclusions

Aerodynamic drag has been identified as a major contributing factor that dictates the performance of a cyclist [2]. This paper proposes to find the optimum cadence that will minimise the drag. The paper discussed in detail an automated manikin and experiment setup that will be used for the study of the unsteady flow behind the cyclist and determine its evolution and effect on the measured drag. The evolution of flow behind the cyclist should provide a better understanding of the mechanism of drag variance due to different cadence.

A preliminary result is obtained for the phase-locked and the fluctuating component of stream-wise velocity and is presented in the paper. Scaling of the free-stream velocity and the cadence proportionally was proposed to reduce the load on the hip motor. In future, the validity of the scaling will be confirmed by running the experiments using a less severe down scaling. Also, as a future refinement the grid points where the measurements are taken will be made finer and the other velocity component (v and w) will also be acquired. Ultimately, multi-component velocity will be measured for a phase-averaged volume behind the manikin to provide a unique insight into a flow field behind a pedalling cyclist.

References

[1] Abbiss, C.R., Peiffer, J.J. and Laursen, P.B., Optimal cadence selection during cycling, *International SportMed Journal*, 2009, vol. 10, no. 1

[2] Kyle, C.R. and Burke, E.R., Improving the racing bicycle, *Mechanical Engineering*, 1984

[3] Lukes, R.A., Chin, S.B. and Hakke, S.J., The understanding and development of cycling aerodynamics, *Sports Engineering*, 2005, vol. 8, no. 2

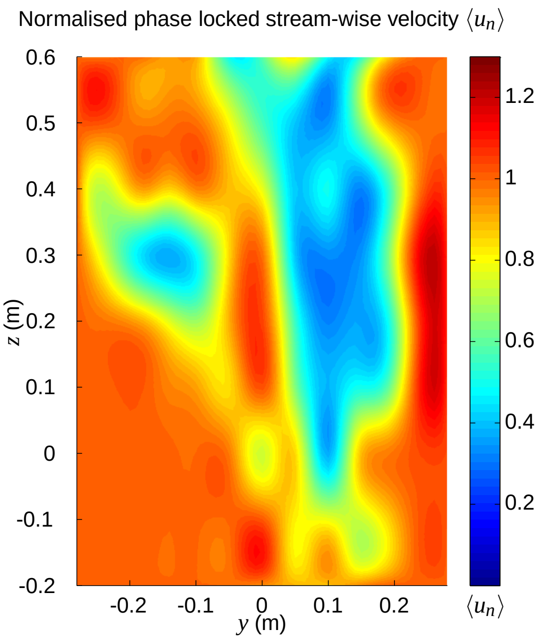


Figure 4: Phase-locked velocity at x = 0.4m plane

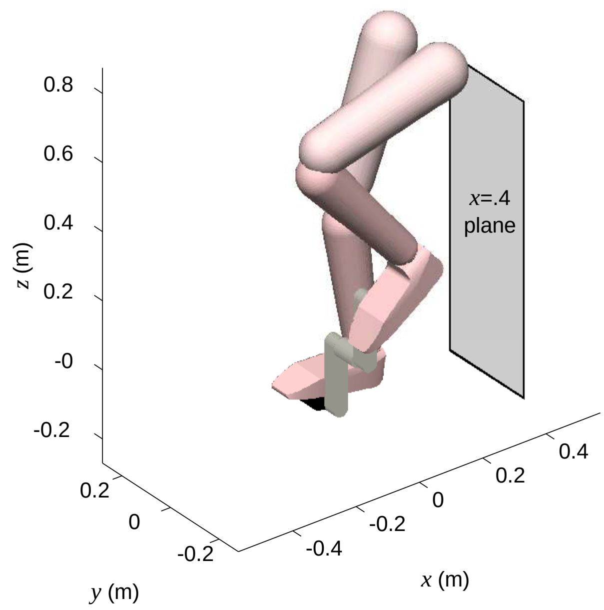


Figure 6: Manikin position at $\theta = 0°$

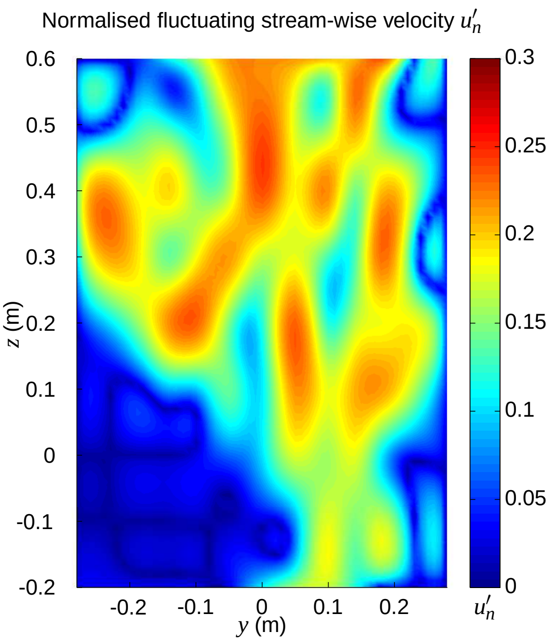


Figure 5: Fluctuating velocity at x = 0.4m plane

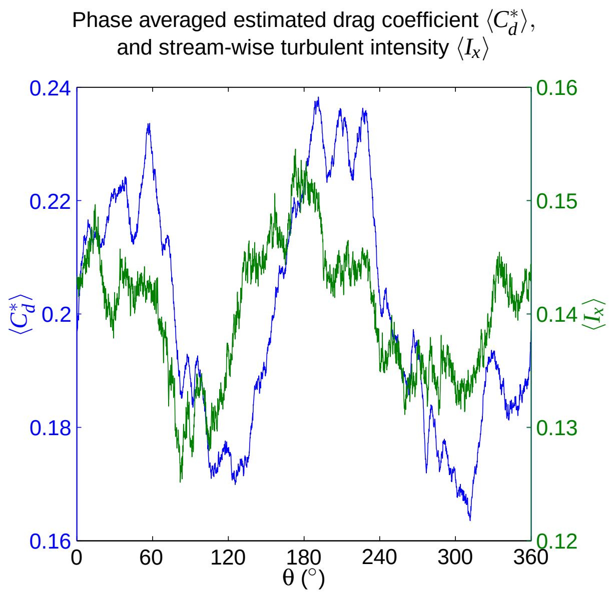


Figure 7: Measurements taken at x = 0.4m plane