Aerodynamic study of a cyclist’s moving legs using an innovative approach

Francesco Pozzetti

30 September 2017

Abstract

During a period of four weeks in September, I completed a research project in fluid dynamics under the supervision of Dr. Neil Ashton, researcher at the Oxford Engineering department.

Prior to my arrival in Oxford and throughout the duration of the research I learned to use some features of the complex and rich package of STAR-CCM+, a software widely used for computational fluid dynamic (CFD) studies.

In the first two weeks I researched recent papers and literature on past experiments and CFD simulations of elite cyclists. I found that most experiments in the past were conducted on a static model to reduce computational costs. The aim of this project was to use a dynamic approach to analyse the model of a cyclist travelling at average race speed of about 45 km/h. This was possible by using a new feature provided by STAR-CCM+, the morphing mesh tool.

Later on, I morphed the mesh to animate a CAD model of a cyclist and study the aerodynamic drag experienced, using the same physics continua as in Crouch[2] and Griffith[4]. Four weeks were just enough for a brief analysis. Nevertheless, it was possible to conclude that the dynamic model does not affect considerably the solution, certifying that for all but the extreme cases, the simplification of a static model is acceptable.

Introduction

At speeds in excess of 50 km/h the aerodynamic resistance is up to 90% of the total resistance experienced by the cyclist [3]. It is therefore understandable that the research around how to improve the aerodynamic profile
of a cyclist is one of the main concerns for teams and researchers. If in the ‘80s a different helmet could signify a victory at the Tour de France for Greg LeMond, nowadays experimental studies are often used as a validation of CFD simulations. In fact, CFD allows for complete control over all model parameters and the quantification of small aerodynamic performance improvements through changes in athlete posture/equipment.

In particular, it has emerged how the RANS shear-stress transport (SST) $\kappa - \omega$ is overall the best model to analyse a time trial. Other methods, such as the Large Eddy Simulation (LES) provides valuable transient information but at a high computational cost, and therefore the only yaw angle tested by I. Conference[3] was 15 degrees. It was also noted how bicycles and their riders are rarely modelled together using CFD due to the computational expense. Thus, one or the other is left out, or if athletes and their bicycles are modelled together, numerous simplifications are made to the model to reduce computational expense.

Experiments such as the ones conducted by Barry[5] in Monash University three-quarter open jet wind tunnel using an athlete and a mannequin show that there is a symmetric wake when thighs of the cyclist are level: this is associated with low vorticity and minimum drag. On the other hand, highly asymmetric flow is observed when the upper legs of the cyclist are at different levels, leading to high vorticity and maximum drag.

However, it is thanks to CFD analysis if Blocken and Topalilar[1] could conclude that while it is well-known in elite cycling that a cyclist riding behind a car experiences a substantial reduction in aerodynamic resistance or drag, the upstream effect by a following car on the cyclist in front of it is also relevant: drag reduction for the cyclist ranges from 3.7% over 1.4% to 0.2% for realistic separation distances of 3, 5 and 10 m, respectively. In particular, at the recommended distance of 10 m set by UCI for safety reasons (never strictly enforced) on a typical time trial stage of 50 km, a cyclist is going to experience a time reduction of 4 seconds.

As processors get more powerful year by year, Crouch was the first to attempt at simulating a dynamic leg movement and comparing it to the static case[2]. He observed how a steady approach works fine at a low frequency of leg movement, since time-scale associated with leg motion is relatively large compared with that of the bulk fluid motion, but as the pedalling frequency is increased this assumption no longer holds: the rotation of the legs will induce local changes in velocity at the legs and influence the local Reynolds number.
STAR-CCM+ features used

STAR-CCM+ is a client-server software: simulation operations are completed by the server and commands are sent to the server by the client. By using this peculiar architecture, users can partition the workload of the simulation set-up and decrease the time required to prepare a simulation prior to solving, focusing on the actual engineering problem.

In my project I used several advanced features available in the software. During the first stages of my internship as I was completing tutorials on geometry, mesh, physics, what I found particularly challenging and rewarding on an academic perspective was the necessity to learn new mathematical and physical models which are part of the third or fourth year courses, such as compressible flow, the finite volume method, Reynolds Averaged Navier-Stokes equations (RANS) and the SST $\kappa - \omega$ turbulence

In the second stage of the project, I learned to use Overset Meshes and interfaces, setting appropriate conditions to ensure that the mesh was as good as possible. Subsequently I was able to morph the mesh: making the body and the surrounding mesh deforming over time in such a way that cell quality is preserved and therefore the overall quality of the simulation. This was particularly challenging as the options available are virtually endless. What I deemed to be most appropriate for my model was either to use some control points leaving the displacement option to floating, or to input a user-defined velocity function to explicitly move a boundary region such as a leg over time.

After this assessment, the final stage consisted in setting up the actual model, by approximating a leg with rectangular shapes for the thigh, the calf and the foot and using prisms for the ankle and the knee. The task was to simulate perfectly the rotation of the thigh combined with the rotation of the calf in a coordinate system moving over time. The combination of motions had to ultimately lead to a circulatory movement of the foot. There are probably various ways of doing this: after some careful planning, I decided to use a MatLab script and some pen-and-paper geometry to find a set of points which I then interpolated to find two seven-degree polynomials - one for the thigh, the other for the calf expressing the angular velocity over a full crank-cycle of 0.75 seconds, corresponding to a cadence of 80 rpm. The polynomials were fed to STAR-CCM+ which performed the computations.

This work was necessary because the only way to make a coordinate system rotate with respect to another one (the parent one) and subsequently perform other motions on the dependent system is to explicitly define a rotation: it is not possible, or at least I could not find a way consulting the documentation, to use a set of control points or a table, as these methods do not allow to manage a dependent coordinate system.
Figure 2: An example of morphing with interacting fluid flow

Figure 3: The moving leg completing a crank cycle
Results and conclusions

Interestingly, despite being a relative straightforward motion with only one constraint, the graphs expressing the displacement angles over time of the thigh and the calf are all but ordinary functions. It would be interesting to investigate how changing the size of the pedal or the relative ratio between the thigh and the calf would make these graphs look: arguably, they could sensibly change in shape.

Figure 4: Graphs representing thigh and calf angular displacements. Their derivatives were fed to STAR-CCM+
As legs were aligned, a symmetrical flow regime was observed for both static and dynamic leg conditions. As the legs were moved through the crank cycle to the point that one of the legs straightened, the characteristic asymmetrical flow regime was observed. Crouch[2] is the only academic who published a paper on the topic: he observed how a quasi-steady approximation (i.e. static model) is reasonable for a reduced frequency of up to 0.11. This is good for investigations on elite cyclists in time-trial events.

Nevertheless, I will carry on this project with the supervisor during term time to deepen the research and possibly to find another approach to the dynamic movement problem in cycling.

Figure 5: Contours of static-leg and dynamic-leg streamwise velocity fields for symmetrical low (15 deg) and symmetrical high (75 deg) phases of the crank cycle
References


