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Comparison of the aerodynamic performance of five racing bicycle wheels by means of CFD calculations.

Matteo Pogni*[a], Nicola Petrone[a]

[a]*Department of Industrial Engineering, University of Padova, Padova 35121, Italy*

Abstract

Aerodynamic drag is the main source of losses in cycling so improving the bicycle aerodynamic is a fundamental key factor to increase the performance.

The aim of this research is to evaluate and compare the aerodynamic performance of racing bicycle wheels by means of CFD RANS numerical models: it is based on a previous work that reported the development of the numerical model.

The aim of this work is to assess the capability of CFD RANS simulations to predict the aerodynamic performance of modern racing bicycle wheels. Drag and side forces are resolved over the range of different yaw angles.

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Keywords:

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1. Introduction

Improving the aerodynamic performance in one of the major challenges in the engineering research applied to racing bicycle. In fact, aerodynamic drag is the main source of losses in cycling and causes between 70% and 90% of total losses in flat road pace (i.e., when not climbing) [1]. Moreover, also lateral forces imposed by crosswinds play an important role because they can destabilize the bike itself.

The body of the cyclist is actually the most important source of drag, because of its relevant frontal area [1]. However, it is necessary to improve also the bike's components aerodynamics, which account for about the 33% [1] of the total drag. This quite relevant percentage is mainly due to the wheels and the frame design.

According to *Greenwell, et.al* [3] wheel drag is responsible for 10% to 15% of total aerodynamic drag; therefore improving the design of this component can reduce the resistance of the bicycle by 2-3%. These numbers, in view of the high level required by either the today's competitions or the bicycle market justify the effort involved in cycling components aerodynamics.

The studies available in the scientific literature can be organized in two categories: experimental studies and numerical studies. The former category analyses the changes in the behavior of the wheel~~s~~ [3] due to changes in shape and/or positioning angle [10]. These studies usually consider the isolated wheel supported by means of specific struts~~,~~ However, is some cases the whole bike is considered as well [4]. The latter category tries to simulate the wheel aerodynamics by means of several approaches. For example, numerical studies dealing with different racing wheels were performed using a steady state RANS model, by means of relative reference frame computations to consider the motion of the wheel [2]. Another numerical work [6] models by means of DES approach the whole domain by dividing it into two sub-volumes, one containing the spokes, hub and inner edge of the

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* Corresponding author. Tel.: 39-340-3034800.

E-mail address: matteo.pogni@studenti.unipd.it

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wheel rim, and the other containing the remaining toroidal wheel surface. This partitioning technique makes easier the model setup in case of repeated changes in wheels and rims geometry.

The most widely used turbulence models for RANS computations are: the simple and computationally low cost Spalart-Allmaras model (see, e.g., [6]); the k-ω and the k-ε turbulence models (the latter both in the standard [2] and in the realizable version [7; 2]). Lukes [7] used all these models and the comparison among them showed similar results.

This paper presents the method adopted to build the steady-state RANS model, the setup parameters with special focus on the multi-reference frame used for the simulation of wheel rotation and on the cylindrical region specifically conceived to change the wheel's incidence angle, as described in the previous article by the same authors [11].

Finally, the paper reports the preliminary results of the comparison between five spoke wheels, performed by using the k-ε model.

2. Method

The model used is better described in the previous paper [11]; the program used for the numerical simulations was Star-CCM+ 9.02.007. Initially, the numerical modeling was oriented to reproducing the results presented in a literature study [6] due to the availability of the profiles of different racing wheels: on the other side, simulation model and turbulence model seemed not appropriate for this analysis.Initial tests focused on a disc wheel in order to reduce the number of elements needed for the model.

To obtain a steady-state analysis, we applied the MRF (Multiple Reference Frames) method in which a different frame can rotate (and/or translate) with respect to the laboratory reference frame. By imposing a rotating frame to the region containing the wheel we took into account the effect of the rotation on the fluid around it, without providing a rigid movement to the wheel and an unsteady simulation needing more computational resources.

We also introduced a second cylindrical region to change the angle of the wheel without the need of re-meshing at each incidence angle simulation. Two interfaces were therefore created between the rotating region, the incidence region and the overall fluid region to guarantee the continuity.

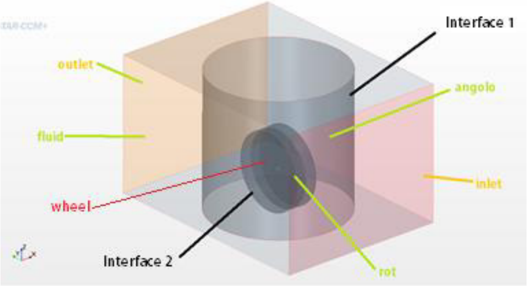

Figure 1 CFD Region and boundary condition

The fluid domain was based on the characteristics of the wind tunnel that we will be allowed to use in the future to test experimentally the wheels: the wind tunnel test section is 2m long, 1,5m wide and 1,2m high.

The model was build using the wheel only, initially without the fork or any support: the mesh was defined using a prism layer mesher near the domain walls and a polyhedral mesher for the fluid domain with a prism layer near the wall region. The mesh was refined by imposing a minimum and mean surface size in the wheel and in both the interfaces, and then by setting a low surface growth rate and increasing the density of the mesh in the two inner regions. The simulations ran on steady state model using a constant density gas (because of the low speed) with a standard K-ε turbulence model with two-layer y+ treatment. The wind speed was 8,94 m/s matched by the wheel rotating speed.

After defining the geometry, the field mesh was created: after a number of preliminary tests, comprehensive of a grid sensitivity study, showed in fig.2, we chose the geometry dimensions.

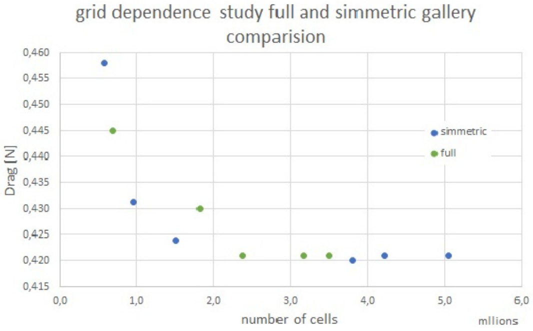

Figure 2 grid sensitivity study

The sensitivity of CFD results from grid size showed in fig.2 was also obtained by means of calculations performed on a halved domain that uses the symmetry condition to halve the number of the cells, comparing the results with the full domain simulation. The wheel used in this test was a disc wheel.

The prism layer mesh has been fixed to 15 prism cells with 1,2 growing rate. These parameters allow for proper values of the y+, keeping it around 1 on the wheel surfaces, as show in the example on fig.3.

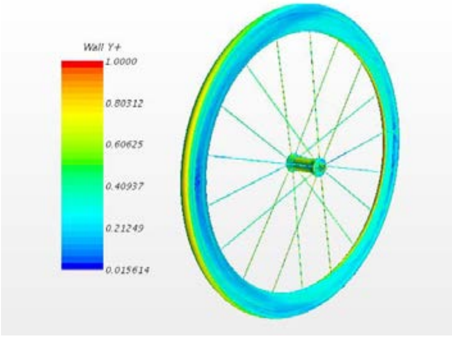

Figure 3 wall+ value for a S4 wheel at 10°

The most used turbulence models in literature were the Spalart-Allmaras model [6;9], the k-ω and the k-ε (standard and realizable version): Lukes[7] used and compared these models obtaining similar results, after a model comparison on a basic disc wheel we decide to use the Standard k-ε model for this paper.

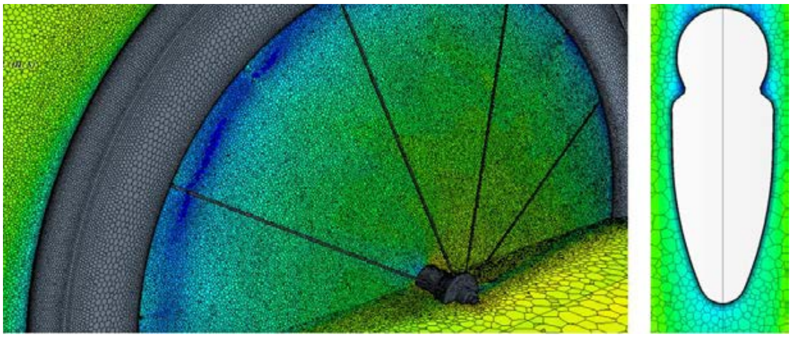

Figure 4 Mesh particulars near the wheel region and prism layer on the wheel profile

The test were conducted at different wheel yaw angles, typically 0°,5°,10°,15° and 20°, higher relative angles won't be useful since

they will be unusual in normal road condition.[8]
The drag is considered in the same direction of the wheel with the side forces in a normal direction as shown in figure 5.

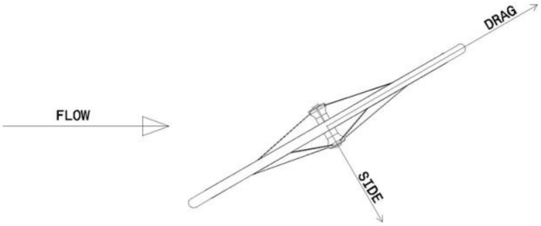

Figure 5 forces direction

The model was partially validated using wind tunnel experimental data available from the literature [9] regarding the Zipp 404 wheel, named S2 in this paper.

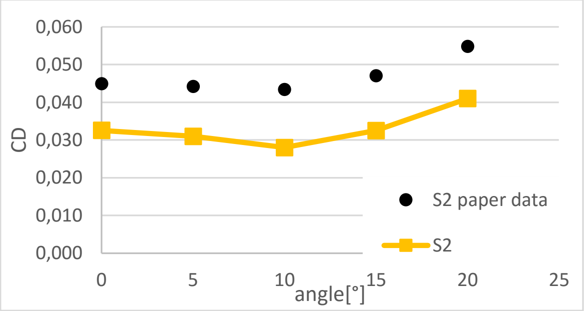

Figure 6 comparison between the calculated cd and the experimental cd of the S2 wheel

The figure 6 shows a Cd comparison between the calculated data and a set of real wind tunnel data retrieved from *Godo et al* [9].
The drag coefficient is calculated using the diameter as the reference area.
It can be seen that the forces are lower than the one showed by the real data, this may be due in part to differences between the boundary conditions applied for the CFD simulations and those present in the wind tunnel.
Considering the wide range of differences between the unknown wind tunnel geometry and balance hardware, the mounting fixtures to hold the wheels, and the differences in testing protocols that the experimental data has been generated from, the agreement with CFD predictions is seen to be highly encouraging.

3. Results and Discussion

We performed the full range of simulations on five different spoke wheels (named from “S1” to “S5”). The geometry of S1, S3, S4 and S5 wheels were directly made available by the manufacturer and the tire profile was obtained using a coordinate measuring machine. Wheels were fitted, when possible, with the same size tire, the profile of the S2 wheel was taken from literature.
The profile and the main characteristics of the wheels can be view in the following image and table.

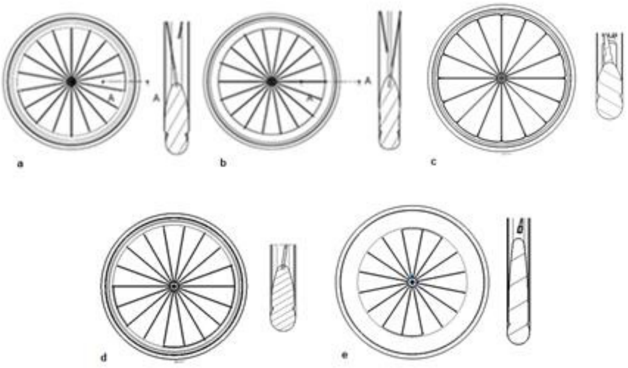

Figure 7 S1 (a), S2 (b), S3 (c), S4 (d) and S5 (e).

Table 1. Wheel details.

Wheel label	Type	Wheel depth with tire
S1	18 Spokes	70mm
S2	18 Spokes	75mm
S3	16 Spokes	50mm
S4	18 Spokes	55mm
S5	16 Spokes	100mm

The other spoke model, named S2, was built using the same hub and spokes and a profile taken from literature [9].
S4 and S3 wheel are low profile carbon fiber high end wheel, the S5 is a low profile aluminum wheel and the S6 is a high profile carbon-fiber wheel, a closed surface geometric model of each wheel was build, eliminating small details that will not interfere with the aero performance but can increase the geometric complexity of the wheel.
The wheels S1, S2, S3, S4, and S5 were fitted with flat spokes depending on the model.

Table 2. Drag and side forces results for the spoke wheel,.

	S1		S2		S3		S4		S5	
Angle [°]	Drag [N]	Side [N]	Drag [N]	Side [N]	Drag [N]	Side [N]	Drag [N]	Side [N]	Drag [N]	Side [N]
0	0,55	0,02	0,54	0,16	0,53	0,00	0,64	0,00	0,49	0,00
5	0,52	0,69	0,53	0,88	0,55	0,48	0,60	0,44	0,43	1,53
10	0,45	1,53	0,47	1,53	0,56	1,07	0,52	1,06	0,08	2,75
15	0,41	2,59	0,50	2,43	0,57	1,68	0,61	1,73	0,08	4,43
20	0,46	3,39	0,68	3,39	0,63	2,19	0,65	2,42	0,25	5,78

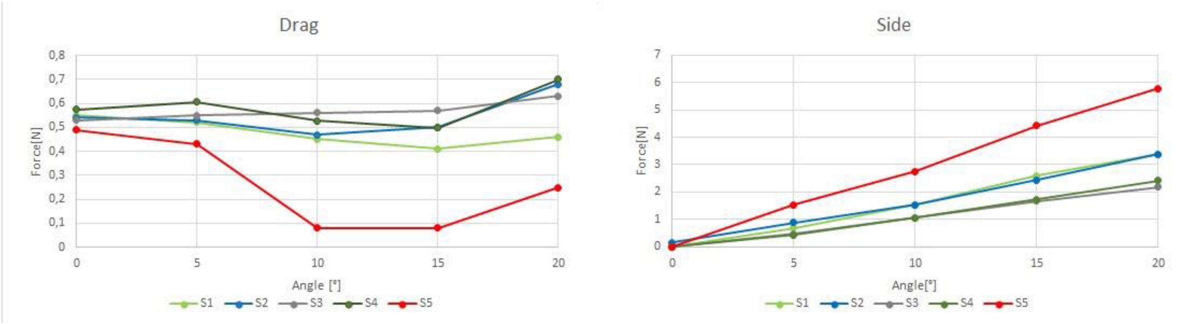

Figure 8 Drag and side forces graphs for Spoke wheels

In general, a considerable variation is observed between wheels. As the depth of the rim increases, the extent of the total drag minimum is also seen to increase. This drag minimum is seen to occur for the S2, S4, and S5 at between 10° and 15° yaw, which is close to the real world conditions; In fact this range of yaw is considered to be predominantly experienced by cyclists, and is regarded as a performance target by wheel manufacturers.

The higher the wheel depth is the high will be the side forces, generally side force were observed to increase in a nearly linear fashion with respect to increasing yaw, as stated in previous works.

Considering the fact that the wheel tested are various and extremely different by the shape of their profile we can still compare the closest ones.

The S1 and the S2 models present a similar rim depth, we expected S2 wheel to have a lower drag at 0° due to the smaller frontal area; this hypothesis was confirmed by the simulation, the S1 anyway wheel present better performance for each angle tested over 10°, the side forces are similar, probably due to a similar wheel depth.

The S3 model is the closest to a typical road bike wheel’s profile, this wheel does not present the typical decay of the drag force between 10° and 15° degrees as the other wheels do, meanwhile the performance at 0° it had a similar performance of the low profile wheel and this wheel show less variation in the drag forces at the variation of the wind angle than the other wheel tested, the side forces were the lowest found among these wheels.

The S4 wheel is a low profile “aero” wheel, it present a higher drag force than expected, especially comparing it to the S3 wheel, the S4 presents better performance only for angle greater than 10°, meanwhile the side force is comparable with the behavior found in the S3 wheel

the high profile S5 wheel presents a high decay at 10° too, it shows better drag performance for every angle tested, it also present a high side forces (that is less than an half of the force experienced by the full disc wheel [11]).

4. Conclusion

In this work, CFD was used to explore the complex and unsteady nature of airflow around five bicycle wheels. The CFD predictions of drag forces showed significant differences between wheels. For yaw angles in the range of 5 to 15 degrees, (those most commonly experienced by cyclists in practice), the deeper rim wheels offered a clear advantage on drag force, balanced by a higher side force.

The preliminary results obtained by the present method show a satisfactory capability to describe the qualitative aerodynamic behavior of racing bicycle wheels, the complete validation of numerical results will be possible only after a wind tunnel testing sessions scheduled later this year.

Owing to the flexibility of this methodology, it is now possible to use CFD to provide more answers on some of the open questions within the competitive cycling.

The future developments of this work, other than the wind tunnel validation, includes a unsteady testing at angles around 10° to clarify the behavior of the wheel at that critical angle and the development of a performance index based on the wind averaged drag method.

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