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

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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 work is to assess the capability of CFD RANS simulations to predict the aerodynamic performance of modern racing bicycle wheels. This paper describes the design and development of a numerical model for the resolution of the airflow field surrounding four different racing wheels. Drag and side forces are resolved and compare to experimental data (and other simulation results) taken from the literature.

*Keywords:*aerodynamics; bicycle racing wheels; CFD;

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.

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 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.

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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 wheel rim, and the other containing the remaining toroidal wheel surface. This partitioning technique make 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., [4]); 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 firstly 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 ~~a~~ cylindrical region specifically conceived to change the wheel's incidence angle. Then, the results of the grid sensitivity study and the motivations for the turbulence model selection are shown as well. Finally, the paper reports the preliminary results of the comparison between two discs shaped wheels and two spoke wheels, performed by using the k-ε realizable model and the standard model.

2. Methods

The CFD code used to perform the numerical simulations is the finite volume CD-Adapco Star-CCM+ ® ver. 9.02.007 code. In the first step, the computations were aimed at replicating the results of analyses presented in a literature study [4]. In fact, the work [4] reports CFD predictions obtained for several profiles of racing wheels. On the other hand, some choices operated in [4] (see, e.g., computational grids and turbulence models) seemed to be improvable.

First, the disk wheel profile given in [4] has been considered for the analysis. In fact, this profile is the one among the others available that allows for the minimum cells number. Moreover, it is particularly suited for validation purposes because reference [4] reports for this profile both wind tunnel data and CFD results.

The wheel geometrical model was built by merging the flat disc profile shown in Fig.1, and a wheel hub of known design, as the hub geometry was not described in the paper.

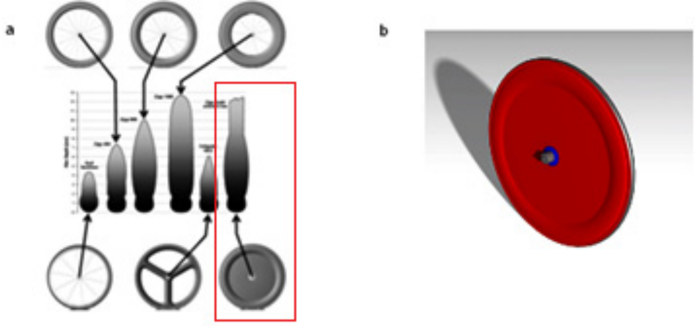

Fig 1 (a) wheel profiles [9] (b) Disc wheel.

This wheel was also tested in a symmetrical domain to further reduce the total cells number: this computational domain was used to test the dependence of results from the grid size. To perform steady-state analyses, the MRF (Multiple Reference Frames) motion approach has been used; MRF technique performs calculations on different reference frames so that a part of the computational domain appears as rotating (and/or translating) with respect to the laboratory reference frame. By imposing the rotating condition to the region containing the wheel it is taken into account the effect of the rotation of the fluid relative to the wheel without requiring the actual rigid motion of the wheel and the corresponding unsteady simulations that need more computational resources.

A second cylindrical region useful to change the positioning of the wheel (i.e., the incidence angle) without the need of re-meshing the whole domain has been introduced as well. Two-interface regions were therefore created between the rotating regions, the cylindrical region and the remaining fluid domain to guarantee the flow continuity (see, Fig 2).

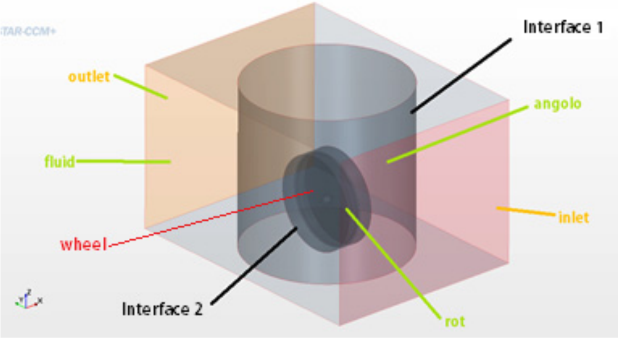

Fig 2 CFD Region and boundary condition

Size and shape of the fluid region considered for the computations were based on the features of the wind tunnel that it will be used 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 includes the wheel only, without the fork or any other strut: the mesh features a prism layer near the walls and a polyhedral cells core for the bulk flow domain. The mesh was progressively refined by changing the minimum and the mean size at both the wheel surface and the domain interfaces, and then by setting a low surface growth rate and by increasing the density of the mesh in the two inner regions. The preliminary steady state RANS simulations ran using a constant density gas (because of the low speed) and the realizable K-ε with two-layer y+ wall treatment for the turbulence closure.

The wind speed was 8,94m/s; the rotational speed was 26.77 rad/s, the same as a bicycle running at 8.94m/s in a straight line.

After preliminary tests, the prism layer mesh has been fixed to 15 prism cells, 1,2 growing rate, 1,1mm total thickness. These parameters allow for proper values of the y+, keeping it around 1 on all the wheel surfaces which is a proper value for the two-layer approach used in the calculations. The grid counts about 3,1million cells.

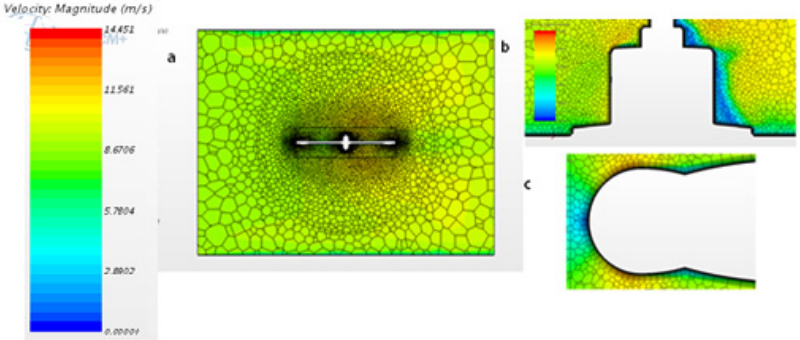

Fig 3 model top view (a) and particular of the prism layer around the wheel (c) and the hub (b)

As stated previously, the sensitivity of CFD results from grid size showed in fig.4 were obtained by means of calculations performed on a halved domain that uses the symmetry (fig. 4b) condition to halve the number of the cells. However, this kind of study was also performed in a bigger fluid domain, using a wider gallery (9m long, 2 m wide for 1,8m height): this latter domain reduces wind tunnel walls effect, but introduces secondary turbulent flow structures that worsen the convergence of the computations.

Note that using the same grid size for both the computations performed on the smaller (Figure 4a) and the bigger fluid domains in the region closer to wheel results in different estimations of the wheel drag. This means that there is a slight flow blockage in the smaller wind tunnel.

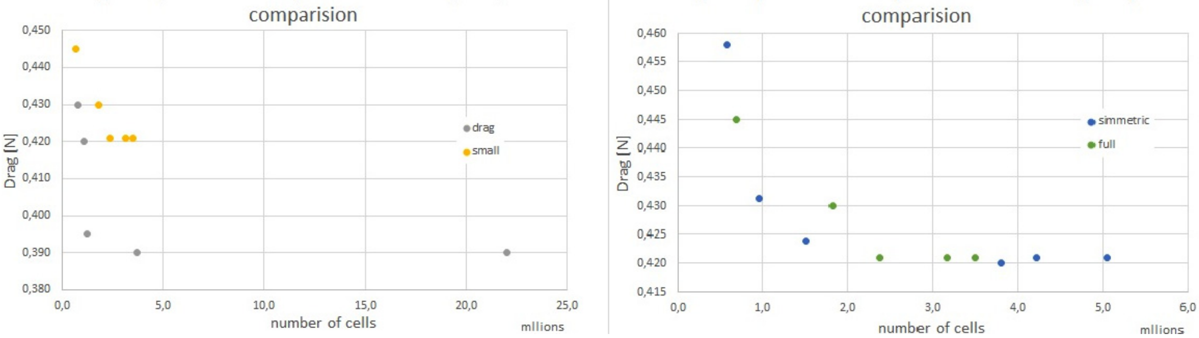

Fig 4 grid dependence study

The symmetrical domain was also used for calculations on a spoke wheel; these data proved to be very useful in the following simulations.

Then steady state computations using different turbulence models has been performed as well. The standard k-ε model predicts drag forces which are lower than the available data. However, the model converges with lower residual values, it takes a little longer time but it generally gives a more stable simulation compared to the other model tested.

3. Results and Discussion

The simulations are performed on the four different wheels showed in Fig.5, which reports two flat disc wheels (the initial one named “D2” and a simpler one “D1”), and two spoke wheels (named “S1” and “S2”). The the geometry of S1 wheel was made available directly by the manufacturer. The wheel features a 22 mm tire and 18 2,5mm flat spokes. The other spoke wheel, named S2, features the same hub and spokes of the S1 model, whereas the profile geometry has been taken from [9]. Figure 6, compares the results obtained for the disk wheels D1 and D2.

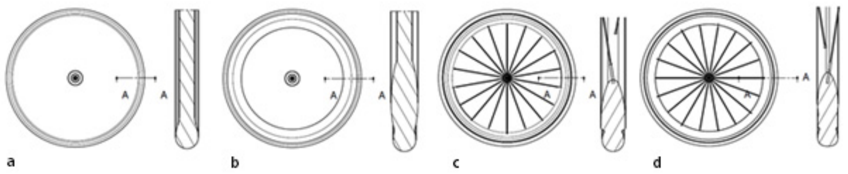

Fig. 5 Disc wheel D1 (a) and D2 (b), S1 (c) and S2 (d).

Note that the two wheels feature the same hub geometry. The D2 disc drag at 0° is higher than that of D1 disk whereas both the D2 drag and side forces are lower than the corresponding parameters related to D1 disk when incidence angles reach values around 10°. It is worth noting that incidence angle different form 0° is the more common real world scenario. [8]

Table 1. Comparison of Drag and side forces for the disc wheels, calculated by using the standard and the realizable k-ε models.

	realizable k-ε				std k-ε 2L			
	D1		D2		D2 STD		D1 STD	
Angle	Drag	Side	Drag	Side	Drag	Side	Drag	Side
[°]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]
0	0,41	0,00	0,43	0,00	0,45	0,02	0,44	0,00
5	0,30	3,55	0,32	3,45	-	-	-	-
10	0,08	7,22	0,01	6,75	0,04	6,74	0,10	7,03
15	-0,27	10,54	-0,36	10,60	-	-	-	-
20	-0,61	14,49	-0,64	14,81	-0,62	14,64	-0,56	14,15

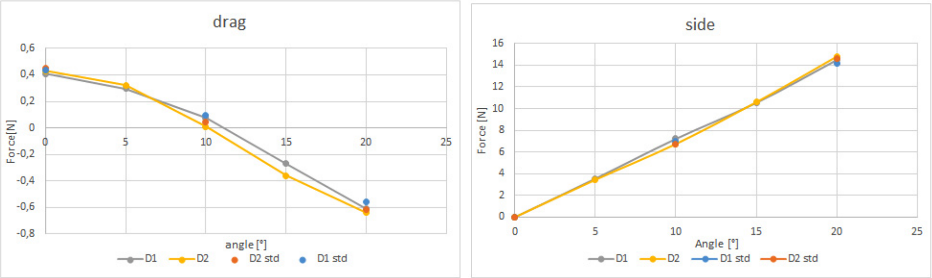

Fig. 6. Drag and side force graphs of D1 and D2 wheels

the computational grid was slightly modified to perform the simulations of the spoke wheels. In fact, due to computational resource limits, it was not possible to use the same setting used for the disc wheels. Therefore, the final grid counts about 4.2 million elements (instead of 16 millions). The sensitivity of the result from the grid size was checked by comparing these results with those obtained by using the symmetrical mesh presented before (the actual spokes disposal is not perfectly symmetrical but the influence is negligible) and showed that results are comparable (with differences of about 0,01 N in drag). The results of the S1 wheel are reported in Fig.8 drag forces behavior, with the growth of the force for angles greater than 10° seems close to the drag behavior obtained in other wind tunnel tests [9]. S2 wheel should have lower drag at 0° due to the smaller tire fitted: this hypothesis is confirmed by the simulation, as clearly notable in table 2 and Fig 9. Taking into account the "hybrid" construction of S2 wheels, the behavior of the wheels is close to what is expected in real world experiments.

Table 2. Drag and side forces results for the spoke wheel, comparing the standard and the realizable k-ε models for the S1.

	S1				S2	
	Realizable		Standard		Std	
Angle	Drag	Side	Drag	Side	Drag	Side
[°]	[N]	[N]	[N]	[N]	[N]	[N]
0	0,55	0	0,55	0,02	0,54	0,01
5	0,54	0,53	0,52	0,69		
10	0,44	1,45	0,45	1,53	0,47	1,53
15	0,42	2,52	0,41	2,59		
20	0,46	3,42	0,46	3,39	0,68	3,39

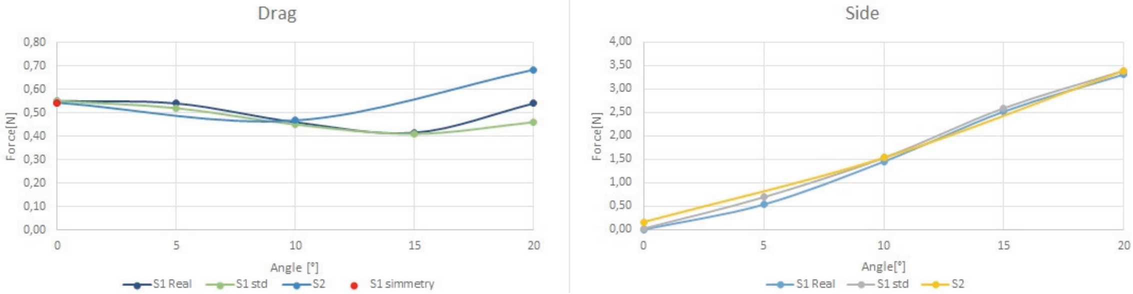

Fig. 7. Drag and side forces graphs for S1 wheels

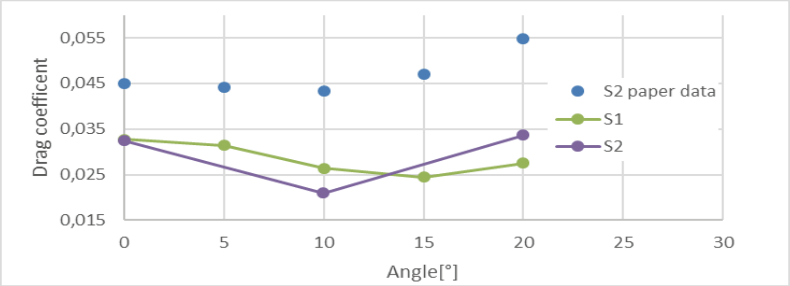

Fig. 8. comparative between the Cd of the models tested and the Cd obtained from the literature

Figure 8 shows a comparison between drag coefficient obtained by wind tunnel tests [9] and the result of present CFD model. The data refer to a wheel that features the same profile as the S2 wheel. It is apparent the quite relevant underestimation of drag coefficient obtained by CFD. However, it is worth noting that the behavior of the calculated drag curve is in good agreement with experiments showing the capability of the present model to capture the qualitative trend of the wheel aerodynamics.

4. Conclusion

The preliminary results obtained by the present method show a satisfactory capability to describe the qualitative aerodynamic behavior of racing bicycle wheels. However, a complete validation of these numerical results will be possible only after ~~a~~ wind tunnel testing scheduled for the future~~.~~

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