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Executive Summary of the Thesis

Computational Fluid Dynamics Investigation and Validation on Bike Wheels Rotation Modeling

Laurea Magistrale in Mechanical Engineering - Ingegneria Meccanica

Author: Federico Amadori

Advisor: Prof. Paolo Schito

Co-advisor:

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1. Introduction

Aerodynamic drag is the greatest obstacle for a cyclist. It accounts for up to 90% of the total resistance when cycling at a speed of 40 km/h on flat terrain. This air resistance is primarily caused by the cyclist's body, which contributes 60% to 82% of the total resistance, depending on the position of the bicycle, while the remaining air resistance is generated by the bicycle. Although aerodynamic drag is only a small part of total drag, optimizing the aerodynamic design of the bicycle is critical to improving the performance of elite cyclists [2]. After all, races can be won or lost by a few seconds or fractions of a second.

In consequence, aerodynamic optimization can be the result of wind tunnel tests, Computational Fluid Dynamics simulations (CFD), and Field tests which can take place indoors or outdoors.

The application of numerical simulations has grown in recent decades, as they serve as a crucial and reliable step in aerodynamic design, complementing experimental campaigns. To enhance the accuracy and comparability of Computational Fluid Dynamics (CFD) with experimental results, numerous turbulence models and numerical schemes have been developed. Among the diverse applications of CFD, simulating the aerodynamics of rotating wheels, especially spoked rims, proves to be particularly challenging.

The rotational motion of wheels alone can contribute to 10% of the total resistance, motivating extensive efforts to improve their aerodynamic performance. However, the absence of a standardized test methodology for wind tunnel experiments and CFD simulations results in a wide range of reported values for the same wheels.

Past investigations on bicycle wheel aerodynamics primarily focused on individual wheels, with testing protocols varying across manufacturers and researchers. This lack of a standardized approach in wind tunnel experiments is also evident in CFD simulations.

Only this work [2] investigated the dependence on the grid resolution, the surface resolution, the turbulence model, and the rotation model. However, the rotation model was investigated only in the Moving Reference Frame, while in CFD there are different ways to consider the rotation within the domain.

This thesis work aims to extend the existing literature on numerical experiments for cycling aerodynamics. Previous studies have mainly used steady-state solvers (RANS) due to time and cost constraints. In this work a computational sensitivity concerning rotation modeling parameters has been investigated, firstly the focus has mainly been on mesh refinement, then on the effects of different rotation approaches. The moving reference model is also validated by comparing the simulated results with a previous wind tunnel campaign.

To enhance our understanding of rotation models, this study explores various rotation approaches, beginning with the lenticular wheel and moving to the spoked wheel. The investigation considers flow at different yaw angles and employs not only the stationary solver with rotating wall boundary conditions and the moving reference frame but also the computationally intensive sliding mesh approach.

Furthermore, a novel application of the rotor disk model is briefly introduced to simulate the flow around the spokes. Additionally, the thesis incorporates Detached Eddy Simulation (DDES) to compare this turbulence modeling approach, which has become more practical with the availability of increased computing power.

In the following sections, the cases used to simulate and analyze these approaches are briefly illustrated. Finally, substantial results and relative observations are reported.

2. Problem description

In the present work, different rotational approaches are investigated. The numerical main characteristic of each method is briefly explained in this paragraph.

2.1. Rotational methods

The choice of rotation model is critical in obtaining high-quality results while optimizing computational resources. The three primary numerical approaches to describe models with rotational parts are Rotating Wall Boundary Condition (RWBC), Moving Reference Frame (MRF), and Sliding Mesh (SM). Moreover, the rotor disk method is introduced as a new method to simulate the spokes of the wheel.

Rotating Wall Boundary Condition The Rotating Wall boundary Condition is a boundary condition where the user can set the patches on which a velocity vector is imposed, as well as the center of rotation, the angular velocity, and the rotational axis. Unfortunately, this condition can be used appropriately only on solid of revolution like the lenticular wheel.

Moving Reference Frame The Moving Reference Frame (MRF) involves placing cells in a rotating reference frame. This method overcomes the issue of resolving the velocity component normal to the surface, which was a limitation of the Rotating Wall Boundary Condition. Specifically, for a surface whose normal is parallel to the rotational wall velocity, the corrected velocity value will be zero in the rotating reference frame but will be non-zero in a stationary reference frame. This approach is achieved by introducing a change of variables to the Navier-Stokes equations.

Sliding Mesh The sliding mesh approach involves physically moving parts of the mesh during every time step, making it the only method presented that achieves actual mesh rotation. Therefore, it is considered the most realistic method for modeling rotating rigid geometries but it comes at a high computational cost. However, this approach has several drawbacks, including the need for an unsteady simulation when using a rotation mesh, as well as the requirement to update the connectivity between the stationary and rotating regions at each time step.

Rotor Disk Method This class allows for cell-based momentum sources to be applied on the velocity field, approximating the mean effects of rotor forces. Spokes are no more meshed but their effects are taken into account giving their characteristic for the radial distance. Indeed the performance of the spokes is inserted inside look-up tables.

Although it is unconventional to use the rotor disk method to model the grooves of a cycling wheel, it is intended to achieve time-averaged effects of rotation independent of position. The rotor disk model is based on the Blade Element Theory (BET).

2.2. Numerical Setup

The geometry of the two wheels was inspired by DT Swiss R460, a commercial aluminum wheel, and modified so that there are two types of wheels, one with twenty symmetrical spokes and one lenticular.

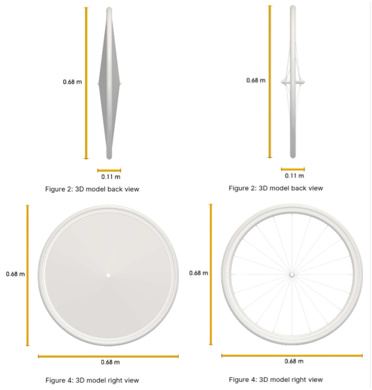

Figure 1: Lenticular and Spoked Wheel

The computational domain is computed starting from the diameter of the wheel to maintain a BR below 1%. The distance of the wheel geometry to the lateral, top, and bottom planes of the domain is 5 ∅, where ∅ is the classic used model for a road bike of $700c$ x $25c$. The upstream and downstream lengths of the domain are 5 ∅ and 10 ∅ respectively.

The computational grid is generated using $blockMeshDict$ which is used to initialize the reference volume around the wheel. The choice of mesh dimension is chosen after a mesh convergence study. The velocity and the rotational velocity are then adapted to the different yaw angles. Indeed for the steady state case, the inlet velocity is maintained constant while the rotational velocity is calculated based on the yaw angle, while for the unsteady cases, the inlet velocity varies according to the setup to create the crosswind direction directly at the inlet. The yaw angles investigated are 0,5,10,15,20 $[deg]$.

3D RANS equations are solved together with the $k-\omega SST$ turbulence model which guarantees optimal stability.

The rotational then is modeled with the following approaches:

Rotational Wall Boundary Condition This setup is adopted as the reference case, the one investigating during the mesh convergence. The rotation is modeled simply using the Rotating Wall Boundary Condition (RWBC) to have a fast and robust convergence and reasonable computational time for every case. The rotational velocity is 41.12 rad/s to have a tangential velocity equal to the uniform velocity at the inlet which is fixed at 15 m/s.

Moving Reference Frame In the first case, a cylindrical region is chosen around the two types of wheels. The width of the cylinder remains constant and it is equal to 26cm, while the radius increases from a value which is exactly the radius of the wheel (0.34cm) then 0.37cm and 0.40cm. The thickness is chosen to be able to contain the wheel even at 20 yaw angle. Indeed for this setup, the cylinder volume containing the wheel remains in the same position while the wheel inside rotates around the z-axis. Moreover, for the 0 yaw angle, another simulation with a cylinder thickness of 11cm is investigated to analyze the sensibility also on this dimension and not only on the radius.

The second case, hence the second shape investigated, is derived from the "stl", particularly the lenticular wheel. In OpenFOAM, there is an option to select a region inside a mesh starting from a geometry file. The geometry used is the lenticular wheel "stl" file distance of 1mm, 1cm, and 5cm.

The third and the fourth cases are simulated only for the spokes wheel. The third one uses the same philosophy as the second but the file selected is the rim and the spokes "STL" geometry.

The fourth case is an application of a hybrid model. In particular, the rotating wall boundary condition is applied to the rim while for the spokes region, the MRF is applied. In this case, a frustum shape is modeled to cover the spokes region. This setup is called MRFg.

Rotor Disk Method For this last approach, only the spoked wheels are investigated because the rotor model can ideally substitute the spokes. One of the geometry files used for the meshing procedure is different, indeed in this case the spokes are not geometrically imported but modeled using the $fvModels$ file inside the constant folder.

Sliding Mesh For the Sliding Mesh approach, the mesh setup is slightly different. Because of the high computational cost of this approach, the quality of the mesh is adapted. The region used is a simple cylinder with a width of 26cm and radius a slightly bigger than the one of the wheels (radius = 35 cm).

DDES Case The application of DDES, in this case, is less related to the study of rotational modeling, but it simulates the structure of the turbulence vortex during a transient scenario. Due to the high computational cost of this turbulence approach, the same mesh setup of the SM is used. For this case, only the case of zero yaw angle is analyzed due to the time needed for each simulation. The rotation model used for this case is the MRF volume resulting from the extrusion of the CAD by 1 mm.

AeroCloud

For this work, the lenticular wheel is investigated and the results are compared to RWBC of OpenFOAM. AeroCloud is an online platform where it is possible to make advanced CFD simulations fast and available to everyone thanks to the meshing and simulation processes that are fully automated.

3. Validation

In this study, the wind tunnel measurements conducted by Belloli et al. [1] are utilized for validating computational fluid dynamics (CFD).

These experiments were aimed to measure the aerodynamic forces on two high-performance wheels. Additionally, a Particle Velocimetry test was performed to reconstruct the flow field around the wheels and examine differences caused by variations in tire shape.

The simulation results demonstrate significant agreement with the wind tunnel simulations. In fact, the values closely align with the range obtained from the testing of the two tires, as presented in Table **??**, where the range represents the difference in results between the two wheels.

Regarding the quality of the simulated flow, the adopted rotational model effectively captures the prominent structures of high-velocity flow generated by the rim, as well as the wake formation behind it, as illustrated in Fig. 2.

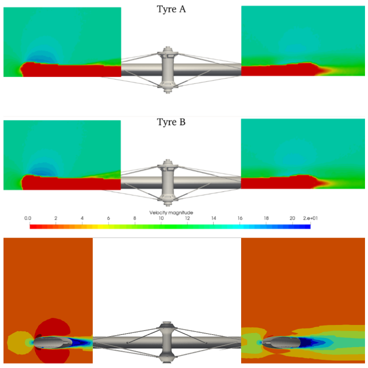

Figure 2: Velocity magnitude of the flow around wheels - Yaw angle = 00 deg at 102 mm over the hub

Validation Results

yaw angle	**0**	**10**	**15**
Drag Exp	0.012	0.008-0.013	0.002-0.015
Drag CFD	0.012	0.006	0.003
Lat Exp	0	0.070	0.01-0.12
Lat CFD	0	0.063	0.074

Table 1: Normalised force comparison for validation [SC_x [m^2]]

4. Results

The numerical results are obtained by averaging the last 400 steps for the steady state simulations, as soon as a trend of convergence is observed, or the last 2 rotations out of 7 for the unsteady simulations.

4.1. Lenticular Wheel

The RWBC is adopted as the reference solution for the lenticular wheel, considering its solid of revolution nature. The utilization of the MRF models, when not optimized, leads to significant differences in computed values and flow predictions. For instance, when the MRF is computed using the cylinder or when the extrusion extends up to 5 cm, a large wake is introduced at the rear of the wheel. This discrepancy is further highlighted in the computed values, which differ significantly from those obtained using the RWBC method. Table 2 presents the comparison, where MRF 1, 2, and 3 denote the cylinder setups with radii of 0.34, 0.37, and 0.40, respectively, while MRF S1, S2, and S3 represent the surface setups with thicknesses of 1 mm, 1 cm, and 5 cm, respectively. The AeroCloud setup is represented by AC, whereas MRFg and MRFs correspond to the hybrid setup with the spoked wheel using "g" and the CAD setup obtained from the spokes using "s," respectively. Conversely, when the MRF is chosen based on the CAD file and the thickness is minimized to 1 cm or even better, at 1 mm, the solutions become comparable. These computed values are further validated by AeroCloud. The unsteady DDES model exhibits good agreement, particularly in flow visualization. On the other hand, the SM approach shows a smaller wake and corresponding lower value, but with increased computational time requirements.

The flow features at 0 angle can be seen in Figure 3.

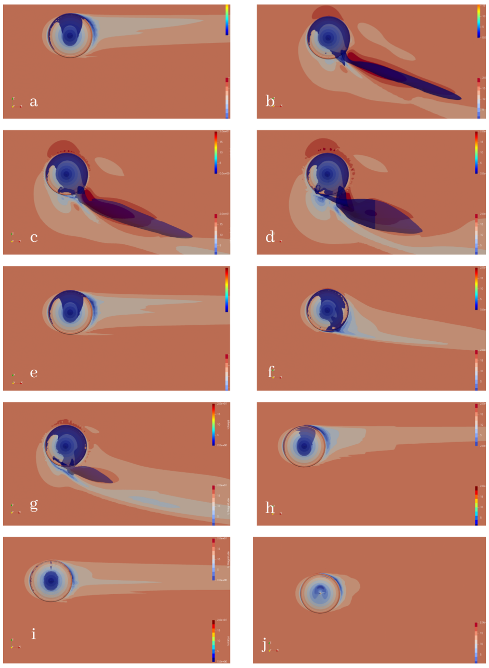

Figure 3: Velocity magnitude of the flow around wheels - From a to j: RWBC, MRF1, 2, 3, MRF S1,S2, S3, AeroCloud, DDES, SM

The same agreement trend is observed when the yaw angle increases, indicating that the setup with a thickness of 1 mm exhibits a favorable compromise with the RWBC solution. Additionally, AeroCloud tends to overestimate the lateral force for other yaw angles, but the flow characteristics remain comparable.

4.2. Spoked Wheel

Similar observations can be made for the spoked wheel. While the computed forces exhibit fewer divergences, as indicated in Table 2, there are significant disparities in flow visualization, with aerodynamic structures resembling those of the lenticular wheel. Similar to the previous case, the cylinder setup significantly influences flow visualization, whereas the surface extrusion setup with a thickness of 1 mm consistently demonstrates favorable quantitative and qualitative predictions. As the thickness increases, the impact of the MRF becomes more pronounced.

The hybrid approach reveals large wake structures a part for the 0 angles. Conversely, the new approach, which directly adopts the spokes as the surface for extrusion, has a positive impact on both computed values and flow visualization at every yaw angle. In this case, the DDES model and SM slightly underestimate the drag force, but the flow structure remains comparable.

The flow around the wheel can be seen in Fig. 4.

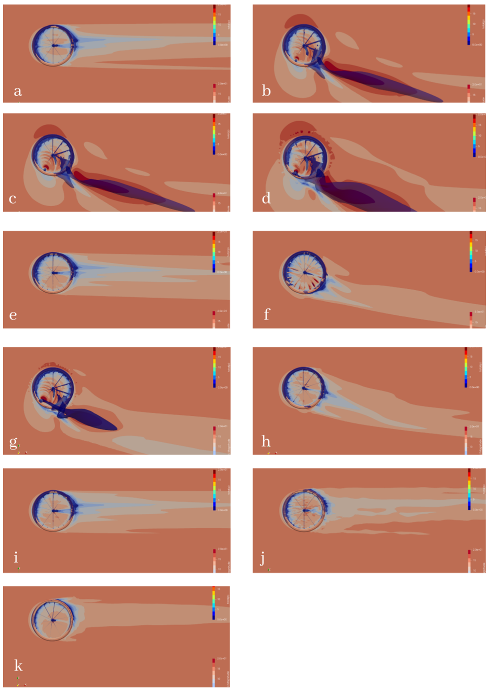

Figure 4: Velocity magnitude of the flow around wheels - From a to j: RWBC, MRF1, 2, 3, MRF S1, S2, S3, MRFg, MRFs, DDES, SM

rotor disk model .The comparison of forces

Drag Force Results

Drag	Lenticular	Spoked
RWBC	0.84	1.62
MRF 1	2.39	1.70
MRF 2	2.33	1.70
MRF 3	1.95	1.67
MRF S1	0.82	1.69
MRF S2	0.89	1.75
MRF S3	1.21	1.38
MRFg	/	1.70
MRFs	/	1.72
AC	0.89	/
DDES	1.04	1.35
SM	0.64	1.45

Table 2: Force comparison for the wheels at 0 yaw angle [N]

for the rim yields interesting results, with the force prediction error limited to below 10% in most cases. Additionally, the C_p plot around the rim profile exhibits a strong correlation with the RWBC case as shown in Fig.5. Furthermore, the flow visualization further confirms this positive trend, indicating that this model warrants further investigation and in-depth analysis.

5. Conclusion

The initial validation of the model used the Multiple Reference Frame (MRF) volume methods and showed good agreement with wind tunnel testing results.

For the lenticular wheel, different approaches utilizing the MRF method were explored, but only the validation approach aligned with the reference case, supported also by AeroCloud results. A quantitative and qualitative comparison of setups revealed inconsistent errors in computed forces without establishing a definitive relationship. Unsteady simulations using the Delayed Detached Eddy Simulation (DDES) and sliding mesh approach demonstrated comparable results.

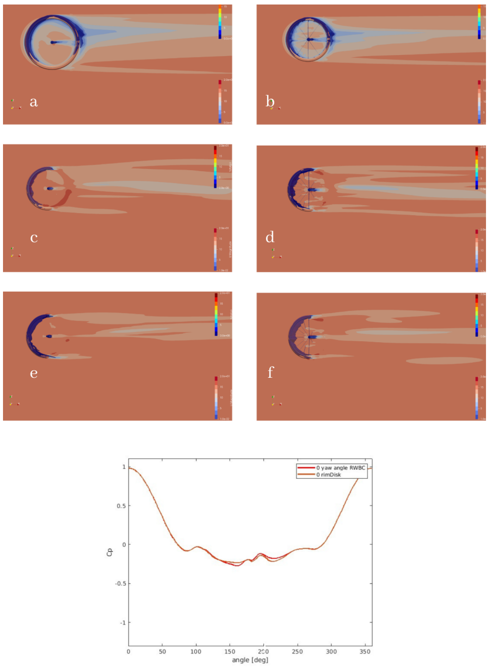

Figure 5: Velocity magnitude of the flow around wheels on the left rotor disk model at 0,10,20 yaw angle on the right RWBC. At the bottom Cp comparison at 0 yaw angle

The thesis further investigated the spoked wheel and introduced new approaches. The MRF volume method using the disc wheel CAD file showed excellent performance in terms of computational time and flow as well as adopting the spokes directly to compute the MRF volume. Inserting volume forces instead of spokes showed promising values for further application.

Overall, the thesis provided insights into the strengths and limitations of various rotational approaches for simulating bike wheels. It highlighted the importance of accurate volume consideration, computational efficiency, and flow behavior in different scenarios. The findings contribute to enhancing the understanding of bike wheel simulations and their applications.

References

[1] S. Giappino G. Porpiglia S. Omarini M. Belloli, P. Schito and C. Somaschini. Aerodynamic investigations of a standalone rotating bicycle wheel. 2020.

[2] F. Malizia, H. Montazeri, and B. Blocken. Cfd simulations of spoked wheel aerodynamics in cycling: Impact of computational parameters. 194:103988, 2019.