Bicycle Wheel Aerodynamics Predictions Using CFD: Efficiency Using Blade Element Theory

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The cycling industry has long relied on expensive wind tunnel testing when designing aerodynamic products, particularly in the context of wheels which account for 10 to 15 percent of a cyclist's total aerodynamic drag. With the recent advent of computational fluid dynamics, the industry now has an economical tool to supplement the wheel design process; however, the complex nature of rotating spoked wheels requires high resolution meshes to model at acceptable fidelity. This research investigates an alternative CFD method that lowers the computational cost of modeling aerodynamic bicycle wheels by modeling spokes using blade element momentum virtual disks. Two CFD models of a HED Trispoke wheel, one with resolved spokes (physical mesh) and one with modeled spokes (virtual disk), are compared to existing CFD and wind tunnel drag coefficient data at various headwind speeds and angles. Preliminary data shows good agreement.

I. Nomenclature

V	=	inlet and ground tangential velocity
w	=	rotational velocity
D	=	wheel diameter
S	=	reference area (pi*D^2*0.25)
Cd	=	drag coefficient (Fx/0.5*density*V^2*S)
Cs	=	side force coefficient (Fz/0.5*density*V^2*S)
Cv	=	vertical force coefficient (Fz/0.5*density*V^2*S)
Fx	=	X component of forces
Fy	=	Y component of forces
Fz	=	Z component of forces

II. Introduction

Elite sports like professional cycling oftentimes have their victors decided by the slimmest of margins. For example, in La Vuelta 2020, cyclist Primož Roglič beat competitor Richard Carapaz by a mere 24 seconds after 72 hours of racing. Because of these slim margins of victory, engineers and cyclists have mutually recognized that aerodynamics optimization is key to winning bike races. Roglič's victory over Carapaz exhibits a time gap of less than 0.01 percent and is a perfect example of where marginal aerodynamics gains could have altered an outcome. Previous research by Godo[1] et al suggests that 90 percent of a cyclist's resistance is attributed to aerodynamic drag, with the wheels contributing 10 to 15 percent of this figure. Furthermore, research by Greenwell[2] et al suggests that geometric optimization of bike wheels could reduce a cyclist's total drag on the order of 2 to 3 percent. Efforts to optimize aerodynamic bicycle wheels typically involve investing hundreds of thousands of dollars into wind tunnel testing; however, CFD is becoming an increasingly popular supplemental design aid as. Buckley[3] writes about how Cervélo has been testing in the wind tunnel since the 1990s, investing hundreds of thousands of dollars per annum to make

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incremental design improvements. Only one decade later would Cervélo adopt CFD due to its ability of more rapidly testing and visualizing designs than the wind tunnel.

More recent CFD studies (circa 2010s) performed by Godo et al demonstrate the efficacy of current CFD techniques by studying the aerodynamics of isolated bicycle wheels at various headwinds speeds and angles, producing CFD data in good agreement with experimental wind tunnel data. High fidelity CFD like that performed by Godo requires extensive computational time, often taking days or weeks depending on number of cores used. This work seeks to reduce said computational time while maintaining simulation fidelity by employing Blade Element Momentum (BEM) Theory, an indirect modeling method traditionally used to accurately predict wind turbines and helicopter rotor aerodynamics. BEM was developed by Rajagopalan[4] et al in 1989 to model rotor blades as a distribution of momentum sources, the strength of which determined by implicit relations between its respective flow field, rotor geometry, and 2D blade aerodynamic characteristics. Essentially, the method assumes that the aerodynamic behavior of each cross-section blade element can be modeled by its corresponding 2D airfoil polar, which can be obtained via experimental data or cheaply generated via RANS simulations. Current BEM code within Star-CCM+ uses virtual disk models to achieve blade loads moderately comparable to field test data, and exhibit flow patterns with expected physical behavior. As it stands, BEM virtual disks are considered a valid tool for simulating bladed geometries at a reduced computational cost.

The idea of introducing BEM into bike wheel CFD comes by observation of bike wheel spokes, which essentially are a kind of blade. Note the HED TriSpoke wheel, which is composed of an airfoil-like rim supported by 3 carbon fiber spokes with cross-sections reminiscent of NACA 0012s. The TriSpoke's NACA 0012-like spoke geometry makes it an ideal candidate for BEM experimentation as the NACA 0012 has a demonstrated history of BEM success. In this work, two CFD models of a HED Trispoke wheel, one with resolved spokes (physical mesh) and one with modeled spokes (virtual disk), are compared to existing CFD and wind tunnel drag coefficient data at various headwind speeds and angles. Preliminary data shows good agreement.

Fig. 1 HED Trispoke side-view, rim cross-section, and spoke cross-section

III. Methodology

A. Spoke Analysis

The HED TriSpoke "blade" geometry is reverse engineered in SolidWorks CAD using the spoke cross-section from Figure 1 with a normalized chord length of 1m. The 3D model is imported as a Parasolid into Star-CCM+, where it is meshed in 2D using the tetrahedral mesher. An overset mesh is used to allow for easy Angle of Attack (AoA) rotation controlled by Java macros, which further reduces the computational cost by eliminating the need to re-mesh.

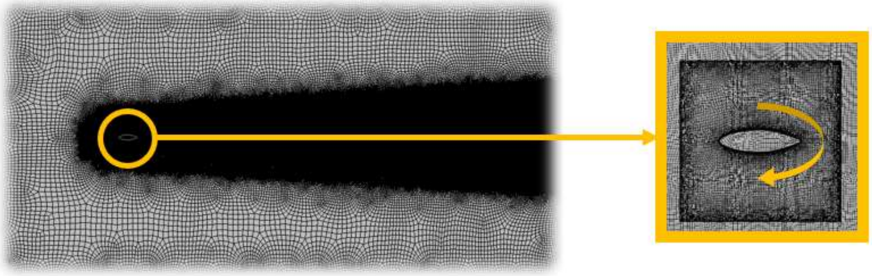

Fig. 2 Spoke Analysis 2D rotating overset mesh

BEM virtual disk models require drag coefficient, lift coefficient, AoA, and corresponding Reynolds number data to model the blades on the interpolation grid, thus a Design Manager study is conducted to acquire all such points for the HED TriSpoke spoke geometry. The study consists of a range of Reynolds numbers from 100k to 500k with a step size of 20k, and a range of AoAs from 0 degrees to 180 degrees with a step size of 3 degrees, resulting in 1500 designs. Solver settings include segregated flow, constant density, single-equation Spalart–Allmaras (SA) turbulence model, and RANS.

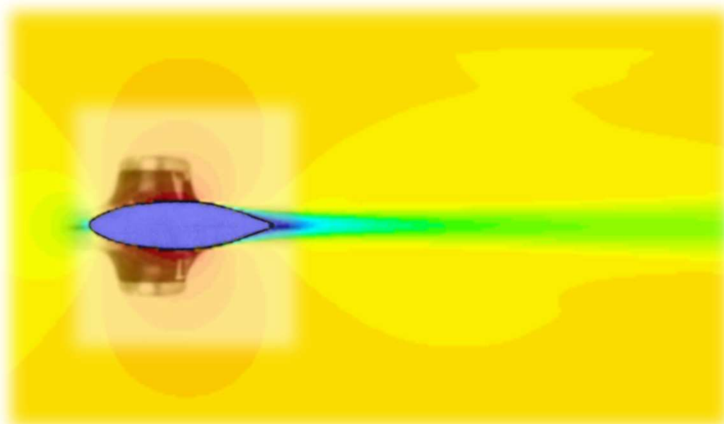

Fig. 3 Spoke velocity profile at 100k Re and 0 degrees AoA with cross-section overlay

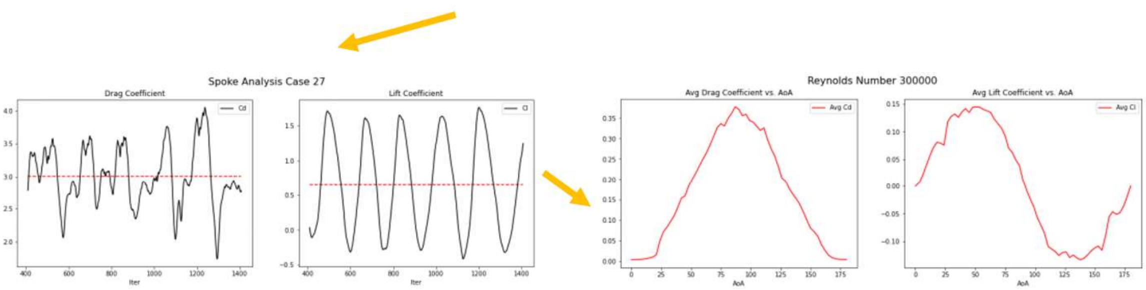

Fig. 4 Example 2D airfoil polar generation workflow

Post-processing all 1500 DM cases requires sweeping Star-CCM+ log files using Python to generate the airfoil polars for each case. Figure 4 exhibits how the code first parses through all simulation data and tabulates raw drag and lift coefficients versus iteration. The dotted red line is the averaged solution, which is then finally used to generate the averaged airfoil polar for each Reynolds number.

B. Mesh Refinement

The Trispoke rim, hub, and tire geometry is reverse engineered using an image of the cross-section, known reference measurements, and a nominal wheel diameter of 0.678 meters. Two CFD models of the HED Trispoke wheel are considered:

1) Spoke Resolved – spokes are fully meshed according to known dimensions
2) Spoke Modeled – spokes are modeled using Star-CCM+ virtual disk with identical dimensions

To eliminate potential sources of error while experimenting with the modeled spoke approach, the Wheel Analysis computational domain closely mirrors that of the computational domain employed by Godo et al. Boundary conditions are made to replicate real-world bike racing conditions. A uniformly distributed velocity inlet introduces air at 30mph at cross-headwind angle of 10 degrees. A pressure outlet exhausts the flow with an extrapolated backflow condition. The side and top planes are modeled as symmetry planes, and the no-slip ground plane tangentially translates at the same velocity as the incoming air, *V*. The wheel is set to rotate using an overset mesh at rotational velocity *w,* as if the wheel were rolling at 30mph.

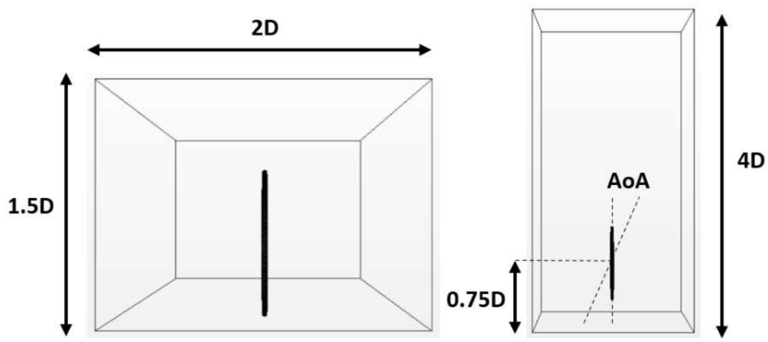

Fig. 5 Computational domain front-view and top-view

A mesh refinement study is conducted using the Spoke Resolved model to determine drag coefficient convergence in terms of mesh cell count. Mesh refinement results show convergence by 6-8 million cells, which is in line with results from Godo[5] et al who uses 6 million cells when modeling the Trispoke. Figure 6 shows the final converged mesh size used for both 1) Spoke Resolved and 2) Spoke Modeled. For each case, two areas of refinement were added in the wake and spoke regions.

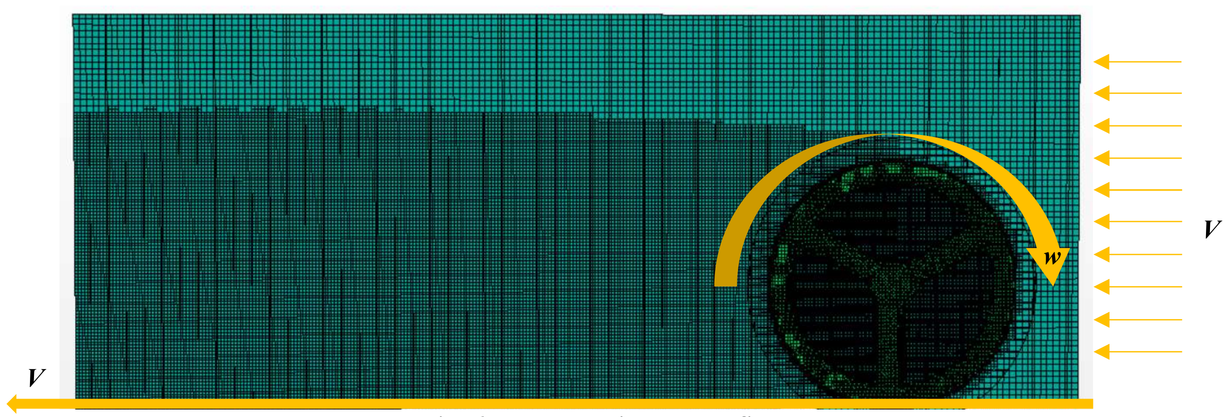

Fig. 6 Mesh used in mesh refinement study

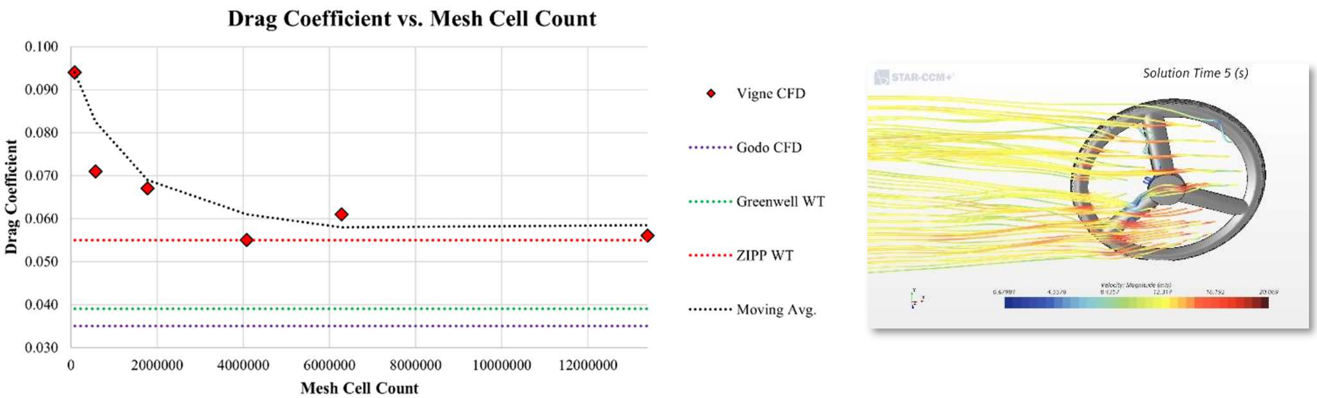

Fig. 7 Mesh refinement study results and streamlines

The mesh refinement study shows good agreement between CFD and wind tunnel data. There is a 5 percent margin between our CFD drag coefficient and Zipp's wind tunnel drag coefficient. While this is a positive indication of a successful model, further experimentation is needed to confirm these results. In the end, a grid density of roughly 8 million cells was determined to be the optimal setup for Wheel Analysis. Streamlines appear to be healthy since high frequency turbulence can develop in the spoke region.

C. Wheel Analysis

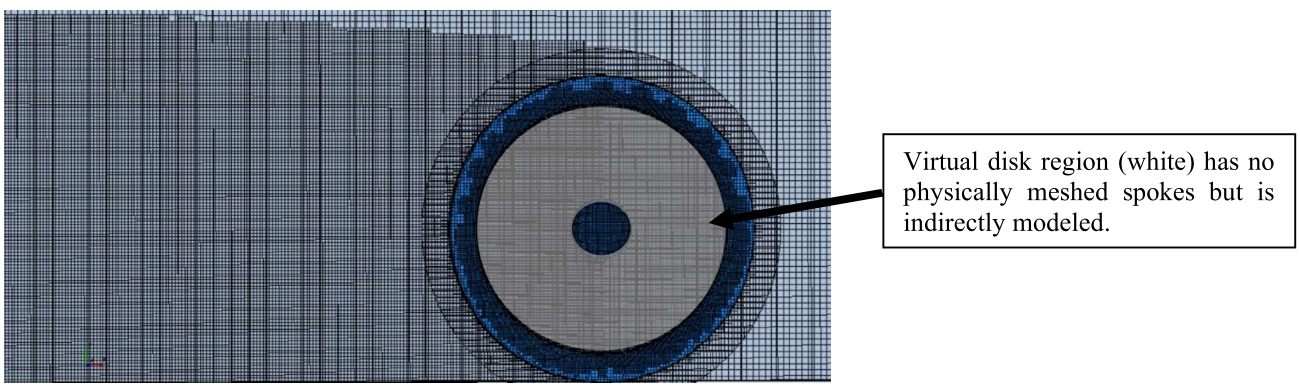

Fig. 8 Spoke Modeled mesh domain

Wheel Analysis was performed at 10 degrees AoA and 30mph inlet velocity using the same computational domain as Mesh Refinement. Both Spoke Resolved and Spoke Modeled cases use 8 million cells. Each case is transient and operate with second order temporal discretization with a time step of 5. The mesh for Spoke Resolved is described by Figure 6. The mesh for Spoke Modeled can be seen in Figure 8. Note there are no physical spokes being meshed in the Spoke Modeled case since the virtual disk models the spokes as a distribution of momentum sources, the strength of which determined by implicit relations between the respective flow field, rotor geometry, and 2D blade aerodynamic characteristics as determined in Spoke Analysis. Preliminary results appear to be in good agreement. Further work is required to confirm a reduction in computational time.

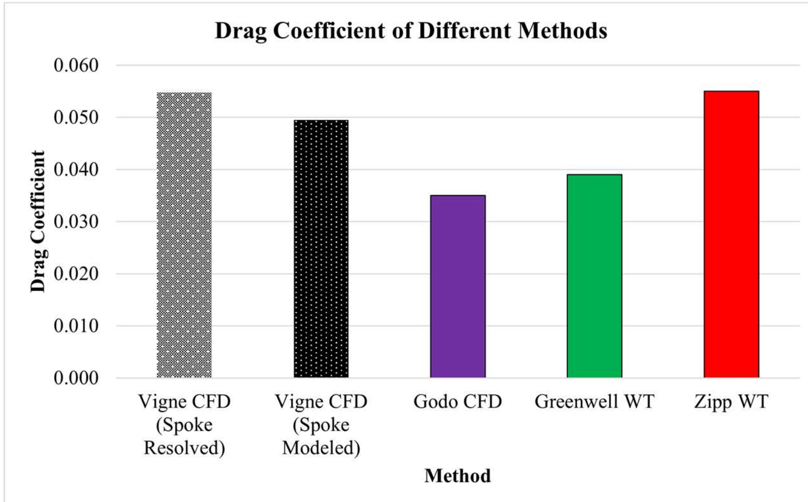

Fig. 9 Drag coefficient comparison of HED Trispoke wheels at 30mph and 10 degrees AoA

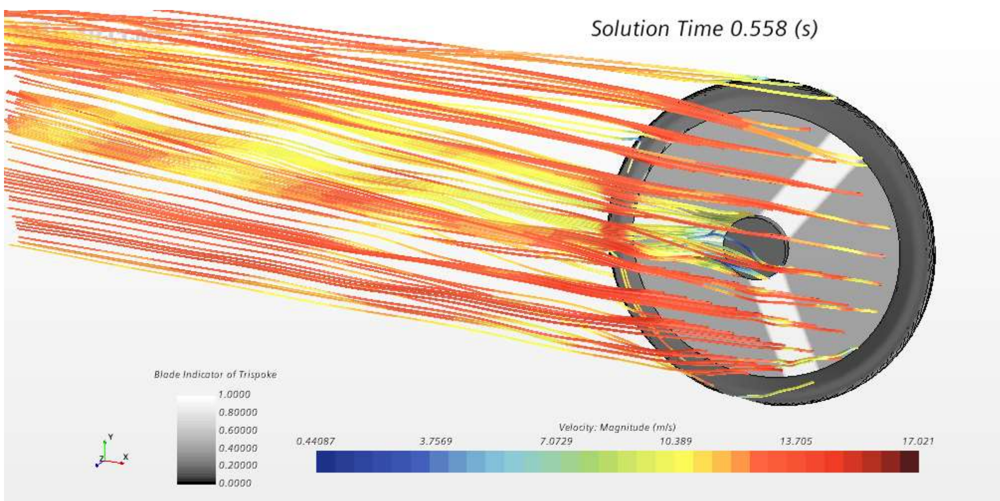

Fig. 10 Blade Modeled streamlines with virtual disk shown as "Blade Indicator"

IV. Discussion

Preliminary data of both Blade Modeled and Blade Resolved show good agreement in the critical 30mph and 10 degree AoA configuration. Figure 9 shows that both CFD models align with previous CFD work from Godo[6] et al and wind tunnel data from Greenwell et al and Zipp. Figure 10 shows visual signs of fluid interaction with the virtual disks, despite them not being fully resolved as a mesh. Further confirmation of this method's efficacy is needed and future works will address force contributions (forces caused by tire, rim, hub) and force distributions (x-forces, y-forces, and z-forces) in more depth.

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