Influence of the wheel rotation on underbody flow and aerodynamic forces of high speed train

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Abstract

The influence of wheel rotation on underbody flow and aerodynamics on high speed train were numerically investigated by using Reynolds averaged Navier-Stokes equations (RANS). Two different conditions including stationary and rotating wheels in CRH3 complex train were calculated, running 380 km/h in the open air. Furthermore, analyses on underbody velocity field, pressure coefficient on bogie sections, wake and leeward vortex structure affected by rotating wheels are performed. The comparison shows that drag coefficient decreases about 1\% when wheels rotating. In the rotating condition, the lift forces of train bodies are reduced, especially the bogie sections. The velocity around the tail car’s bogies increases 13-20m/s due to the wheel rotation effects, and the vortex cores of wake get closer.

Keywords: high speed train; aerodynamic drag; underbody flow; rotating wheels; CFD

1. Introduction

Along with the development of high speed train technology, the running speed has increased a lot. The aerodynamic problem of high speed trains becomes significant. Previous researches have shown that the drag of bogie sections takes 30\% of the entire train [1]. Understandings and analysis of the real underbody flow field is essential to aerodynamic drag reduction [2]. Additionally, in the wind tunnel tests and most numerical simulations, the wheel is stationary. Huang pointed out that the fluctuation of the pressure peak point on an isolate rotating wheel lead to the changes in the aerodynamic drag [3]. Zhao [4] applied DES method to simulate the static wheel and
rotating wheel, and results showed the wheel rotation generated about 5% drag coefficient difference. The wheel rotation affects the distributions of local velocity and pressure, and also directly affects the wake of the high speed train. Consequently, it is important to study the influence from wheel rotation on the flow field around bogie sections and the wake.

2. Numerical models, mesh and setup

2.1 Numerical models

The full scaled CRH3 train is chosen as the numerical model. The train model consists of three cars including the head car, the middle car, the tail car, and all the main components underneath the train including bogie sections and tracks. The head and the tail are power cars, and the middle is trailer car. The bogies are numbered from 1 to VI (Fig. 1.(a)), and bogies I,II,V,VI are the power bogies while bogies III,IV are trailer ones. Fig. 1.(b, c) gives the structures of these two kinds of bogies. Since the brake discs share the same rotating shaft with the wheels on the trailer bogie, the brake discs also rotate at the wheels’ rotational speed.

2.2 Computational domain and mesh

In this paper, two different conditions including stationary and rotating wheels were calculated, running 380 km/h in the open air. The compressibility effect is weak, so it is ignored in this paper. Fig. 2.(a) shows the computational domain. Taking H, L, B as the height, length, width of the train, the height and width of computational domain are 10H and 17B respectively, the length between the inflow and the train nose-tip is L, and the length between the rear end of the train and the outflow is 4L.

This paper adapts mixing mesh showed in Fig. 2(b). The mesh for the outer field is the hexahedral trimming mesh, and the mesh near the wall is prism mesh. The grids around train body, bogies and the tracks are refined to improve the simulation accuracy. The boundary mesh includes 5 layers and the total number is 3.8 M.

2.3 Setup and computational conditions

This paper uses the RANS model with Realizable $\kappa$-$\varepsilon$ two-equation turbulent models for the computations, and adopts the SIMPLE to solve the discrete equations. Take the train’s running velocity along X axis as 380 km/h. There are two different computational conditions, wheel rotation and stationary.
3. Verification of the rotating wall method

This paper adopts the rotating wall boundary condition to simulate the wheel rotation based on RANS. An isolate wheel whose width-height ratio is 1:8 is used to validate the accuracy of rotating wall boundary by comparing with the data of the reference [5].

The comparison of present simulation and data in the reference [5] is in Fig.3. It can be seen that in the range of 0°-90° and 270°-360°, the three curves agree well. In the range of 120°-180°, the static pressure coefficient (Cp) of wind tunnel test is negative, while the CFD results are positive. Especially near 100°, the difference between numerical calculation and wind tunnel test is apparent. There are two major reasons. Firstly, the wheel contacts the floor in the range of 80°-100°, and in this section the computational model differs a lot from the experiment one. Secondly, it’s difficult for RANS model to capture Cp where the wheel contacts floor.

4. Results

4.1 The comparison of drag coefficient (Cd) and lift force

Fig. 4 gives the Cd of different cars for wheel rotation and stationary. The rotation of wheels has little effects on the steady Cd. The Cd decreases about 1% when the wheel rotating. The difference between stationary and rotation from head car is 0.003, the middle car’s difference is 0.002, and the tail car’s difference is -0.002.

Fig.5 indicates the difference of lift force for different car bodies (the stationary condition is the base, and all the following comparison are obtained by stationary condition minus rotating condition), which are separated to eight parts for each car. For the head car, the wheel rotation affects bogie 1 section (Head-2) obviously with a decrease of 292 N. When the wheels rotate, the lift force descends about 257 N on the Middle-3. The wheel rotation has a marked impact on the lift force for the tail car, especially for the bogie 7 section (Tail-7) with a diminution of 682 N. This kind of change is due to the difference between wheel rotational velocity and the flow velocity. It can be predicted that the lift force of tail car will decrease more if increasing the number of car carriages.
4.2 The comparison of flow field underneath the train

Fig. 6 gives the distributions of the velocity on section line underneath the train. It can be seen that wheel rotation affects the flow velocity around bogie sections. In bogie Ⅰ section, the flow velocity increases 6 m/s. And the maximal increment of flow velocity around bogie Ⅱ section is about 14m/s. The difference of velocity flow underneath the middle car between two conditions becomes gently. Compared with the head and middle car, the wheel rotation has an intense effect on the local flow velocity of tail car’s bogie sections. Around bogie Ⅴ section, the peak value of velocity variation is about 20 m/s. And the velocity increases 13 m/s in bogie Ⅵ section. After the nose-tip compression, the flow arrives bogie Ⅰ section with a velocity above 80 m/s. The difference between the flow velocity and wheel rotational velocity is much less. But in bogie Ⅴ section, the flow velocity has dropped to 20 m/s, and the difference is quite great.

Since the underbody structures are complicated, the flow is severely disturbed by the bogies, tracks and wheel rotation etc., displaying evidently the vortex characteristics. Fig.7 gives the vorticity distributions on different horizontal sections in the flow field underbody the train. These sections are between the train and the tracks. At Z=0.14 m, the vortices generating at the leading edge of bogie Ⅲ are induced by the flow separations. The strength of the vortices in bogie Ⅰ section is significantly higher than the other five bogie sections. As the distance between the bottom of the train and the track increases, the strength of vortices weakens gradually. From the differential chart it can be seen that the vortices underbody the tail car change acutely when the wheel rotating. These changes result from the wheel rotation effects of bogie Ⅴ. The difference between the flow velocity in bogie Ⅴ and wheel rotational velocity is great enough to affect the flow field behind bogie Ⅴ.
The wheel rotation can accelerate the local flow velocity. The acceleration effect of bogie VI has an influence on the velocity and vorticity field (Fig.6, Fig. 7). In the meanwhile, the wake and the pressure near tail car’s nose-tip are also changed. This is one of the reasons that wheel rotation affects the aerodynamic drag. Fig. 8 shows the wake of trains in the flow direction. Two vortexes are dissymmetric for the power bogies’ dissymmetry. The horizontal distance between these vortex cores is based on the critical point theory. Along the flow direction, the horizontal distance of two vortex cores rises gradually. Comparing with the stationary condition, the vortex cores get closer when wheels are rotating.

![Fig. 8. (a) The wake of high speed train in stationary condition; (b) The wake of high speed train in rotating condition.](image)

The pressure distributions on bogie section are also influenced by the wheel rotation. Fig. 9 gives the distributions of Cp on bogie II section. When the flow arrives bogie II section, the vortices around section B are induced by the flow separations, and there is a low-pressure area on section B. Then the flow velocity decreases rapidly due to the bogie. The high-pressure area on section C results from the accelerated flow behind the bogie II. Compared with the stationary condition, there is almost no difference of the Cp distributions on section B. In the rotation condition, the velocity of flow behind the bogie is influenced by the wheel rotation. The accelerated flow leads to the high-pressure area on section C narrowing, which directly causes the Cp decrease on section C. This is another reason that wheel rotation makes the Cd change.

![Fig. 9. Distributions of the Cp on bogie II section.](image)

5. Conclusion

The rotation of wheels has little influence on the steady Cd of different cars based on RANS. The Cd decreases about 1% when the wheel rotating. The lift forces of train bodies are reduced while wheels rotating, especially bogie sections. The distributions of velocity and vorticity are different in stationary and rotating conditions. Compared with the head and middle car, the wheel rotation affects the flow field underneath tail car more significantly. The velocity around the tail car’s bogies increases 13-20 m/s due to the wheel rotation effects.
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6. References

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