Numerical Simulation Study on Aerodynamic Characteristics of the High Speed Train under Crosswind

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ABSTRACT

While the high-speed train is running, the side wind will affect its aerodynamic performances which include the drag and lift increase. Especially, when the train encounters strong crosswind, large lateral force and overturning moment will be produced, which directly affects the safety of train traffic. In this paper, the aerodynamic characteristics of a certain type high-speed trains are numerically simulated, where the $k-\varepsilon$ model is chosen as the turbulence model and the pressure correction algorithm is used to solve the RANS equations. Through the simulation, the relations of yaw angle about drag, lift, side force and overturning moment are given, respectively. Moreover, the lateral leeward surface separation situation and the structure of the spatial vortices are given by analyzing the pressure and flow lines at different positions. The comparisons between computational aerodynamic results and experiments are presented, which show that the method in this paper has high accuracy to predict the aerodynamic force of the train in crosswind weather and performances well in crosswind condition with large yaw angle.

Key words: high-speed train, crosswind, aerodynamic characteristics, numerical simulation

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1. INTRODUCTION

With developments in economy and technology, the speed of high-speed trains is increasing rapidly. If the crosswind appears while the trains are running, the stability and safety of the trains will be seriously impaired. In recent years, many train accidents occurred around the world due to strong crosswind. The large side force and overturning moment produced by the crosswind are closely related to the aerodynamic characteristics of the train. Because the cost of the wind tunnel experiments are expensive, and wall interference and blocking effect are obviously great when the wind tunnel test of the 1/8 scaled three-car group model is carry out under a large yaw angle. Thus, it is difficult to check the stability of a high-speed train in wind tunnels.

Nowadays, the computational fluid dynamics method (CFD) has been used to simulate the aerodynamic characteristics of high-speed trains. Especially in the field of conventional aerodynamic prediction and flow field analysis without crosswind [1], CFD method obtained high accuracy results [2]. While the train is running under crosswind, there will be a large separation flow in the leeward area, and which is difficult to simulate with CFD methods. In recent years, some scholars have carried out researches on the aerodynamic characteristics of high speed trains under crosswind conditions [3][4]. Among them, aerodynamic characteristics with simplified CFD model [5], influence of the wheels on train to aerodynamic characteristics under cross wind [6], and aerodynamic characteristics of the train with unsteady crosswind speed [7] were studied. And they all got great effects. However, it lacks useful computational results of complex configuration, and the reliability of simulations under large yaw angle must be improved. Aimed at these shortages, we study the aerodynamic characteristics of scaled model under crosswind conditions with different yaw angles in this paper, where the train model includes bogie, windshield and air conditioning domes. In numerical method and mesh construction part, the RANS equations are solved using pressure correction algorithm. The realizable $k-\varepsilon$ turbulence model is used to simulate the turbulence. The tetrahedral and prismatic type meshes are chosen in space and boundary division with consideration of great matching to turbulence model, respectively. In numerical part, it shows that our results are in good agreement with the experiments.

2. CALCULATION METHOD

2.1 Control equations

The speed of the high-speed train is usually in the range of [200, 350] kilometers per hour. Its aerodynamic simulation belongs to the field of low-speed cases. Thus, the SIMPLE algorithm which is fitted to the incompressible flow is used to solve RANS equations.
The general formula of the Reynolds-Averaged Navier-Stokes equations can be expressed as follows [8,9]:

\[
\frac{\partial \rho \psi}{\partial t} + \text{div}(\rho \mathbf{V} \psi - \Gamma_\psi \cdot \text{grad} \psi) = q_\psi
\]  

(1)

For the continuum equation, it satisfies

\[\psi = 1, \quad \Gamma_\psi = 0, \quad q_\psi = 0\]  

(2)

For the momentum equation in the \(x\) direction, it satisfies

\[\psi = u, \quad \Gamma_\psi = \mu_{\text{eff}}, \quad q_\psi = -\frac{\partial P}{\partial x} + \text{div}(\mu_{\text{eff}} \frac{\partial \mathbf{V}}{\partial x})\]  

(3)

And the momentum equations in the \(y\) and \(z\) directions are similar to equation (3). If the standard \(k-\varepsilon\) turbulence model is used, the turbulence kinetic equation can be written as:

\[\psi = k, \quad \Gamma_\psi = \mu_{\text{eff}} / \sigma_k, \quad q_\psi = G_k - \rho \varepsilon\]  

(4)

The turbulence dissipation equation is presented as:

\[\psi = \varepsilon, \quad \Gamma_\psi = \frac{\mu_{\text{eff}}}{\sigma_\varepsilon}, \quad q_\psi = \frac{\varepsilon}{k} (C_1 G_k - C_2 \varepsilon \rho \varepsilon)\]  

(5)

And the turbulence viscosity coefficient is written as:

\[\mu_{\text{t}} = C_\mu \rho k^2 / \varepsilon\]  

(6)

Be different with \(k-\varepsilon\) model, the coefficient \(C_\mu\) of the realizable \(k-\varepsilon\) model has a non-constant form as:

\[C_\mu = \frac{1}{\left(\frac{k U^*}{\varepsilon}\right)}\]  

(7)

where

\[U^* = \sqrt{S_{ij} S_{ij} + \tilde{\Omega}_{ij} \tilde{\Omega}_{ij}}\]

\[A_0 = 4.04, \quad A_\xi = \sqrt{6} \cos \phi\]  

(8)

In addition, the item \(C_2 \varepsilon^2 \rho \frac{\varepsilon^2}{k}\) needs to be amended.

| TABLE I. CONSTANT COEFFICIENT IN REALIZABLE k-\(\varepsilon\) MODEL. |
|-----------------|---------|-------|------|
| \(C_1\)        | 1.44    | \(C_2 \varepsilon\) | 1.9   |
| \(\sigma_k\)   | 1.0     | \(C_2 \varepsilon\) | 1.2   |

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The numerical calculation method is as follows: the finite volume method is used to discretize the control equations, and the conjugate gradient method is applied to solve the problem. The SIMPLE series algorithm is chosen as the incompressible calculation method. The unstructured grid is used to deal with complex shapes and boundaries. The realizable $k-\varepsilon$ turbulence model is used to simulate the turbulence. There are four general types of boundary conditions: symmetric boundary conditions, inflow boundary conditions, solid wall boundary conditions and exit boundary conditions. The concrete expression of functions, physical meaning and the numerical method can be found in \cite{3, 4, 5}.

2.2 Models and Grids

The numerical simulation model is chosen as 1/8 scaled three-car group model, which includes bogies, windshields, air conditioning shroud and other components. The model is consistent with the experimental shape, and its head of the train is shown in Figure 1(a). The inlet flow velocity is 60 meters per second, and seven side yaw angles are 0, 5, 8.8, 10, 15, 20 and 25 degrees.

The spatial grids of the train are unstructured tetrahedral grids, which are encrypted with fine meshes at the boundary of the curve surface and in the small parts. It is shown in Figure 2. In order to have a better simulation of flow on the surface layer, eight layers of prism grids are constructed near the wall area as shown in Figure 3. The prism grid thickness of the first layer is 1mm. It deduces that the $y+$ value on most of the surface of the train varies from 150 to 200, which matches the wall $y+$ requirements of high Reynolds number turbulence model. Thus, it shows better simulation accuracy which has validated by a lot of numerical calculations. Because the simulation of the aerodynamic characteristics is carried out under strong crosswind, thus the size of the calculation domain should be large enough. The calculation domain is shown in Figure 1(b) with a total of 40 million computational cells, where the note L represents body width of the train.

Figure 1. Train head shape and calculation domain.
3. CALCULATION RESULTS

In this section, the aerodynamic characteristics results of the train are given by parallel calculation with seven yaw angles which are 0, 5, 8.8, 10, 15, 20 and 25 degrees. And the calculation results are compared with the experiments. The side force of the head car is compared with experiment in Figure 4(a). It can be seen that the side force of the head car increases along with the increase of the yaw angle, and the calculated side force agrees well with the experiment. Table 2 shows the side force coefficient of the head car by calculation and experiment. We can see that the calculation results are very close to the experiments, and the maximum error is less than 5%. Figure 4(b) shows the calculation and experimental results of drag coefficient under different yaw angles. It can be seen that the drags of the whole train are in good agreement with the experimental results. The error is less than 2 percent when yaw angle is less than 15 degrees. The error of the calculation is relatively large when the yaw angle is greater than 20 degrees, the main reasons are given as follows. On one hand, the wind tunnel test obstruction increased under large yaw angle, and the wall interference affects the head car. On the other hand, leeward area has serious separation flow under large yaw angle and the current RANS method is not suitable to simulate. Though the error between aerodynamic calculation and the experiments is about 10 percent, it is feasible to give a prediction in engineering.
Figure 4. Comparisons of side force and drag coefficient between calculations and experiments under different yaw angles.

<table>
<thead>
<tr>
<th>Yaw angle (°)</th>
<th>Cf-CFD</th>
<th>Cf-EXP</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.43864</td>
<td>0.42404</td>
<td>-3.33</td>
</tr>
<tr>
<td>8.8</td>
<td>0.80418</td>
<td>0.78124</td>
<td>-2.85</td>
</tr>
<tr>
<td>10</td>
<td>0.93995</td>
<td>0.90897</td>
<td>-3.30</td>
</tr>
<tr>
<td>15</td>
<td>1.55614</td>
<td>1.53154</td>
<td>-1.58</td>
</tr>
<tr>
<td>20</td>
<td>2.25587</td>
<td>2.30641</td>
<td>2.24</td>
</tr>
<tr>
<td>25</td>
<td>3.02872</td>
<td>3.17003</td>
<td>4.67</td>
</tr>
</tbody>
</table>

Figure 5(a) shows lift coefficients of the head car of calculation and experiment under different yaw angles. It can be seen that the lift of the head car increases along with the increase of the yaw angle, and error of the calculation is about 2 percent when the yaw angle is less than 15 degrees. Figure 5(b) shows lift coefficients of the tail car of calculation and experiment under different yaw angles. It can be seen that the tail car lift increases along with the increase of the yaw angles, and error of the calculation is about 5 percent when the yaw angle is less than 15 degrees. When yaw angle is 20 degrees, the lift error of head car between calculation and experiment is about 2.4% (seeing figure 5(a)). However, the lift error of tail car is 12% (seeing figure 5(b)).
Figure 5. Comparisons of lift coefficients between calculation and experiment under different yaw angles.

The flow structure of vortices at the mid-position of each car is shown in Figure 6, where the yaw angle is 10 degrees. We can see that there are two small vortices in the rail and the road side of the first car leeward area, respectively. There are also two vortices around the middle car, where the small one locates in the lower right corner of the body and the big one forms from the entire body of leeward area to ground. With evolution of the vortex, a larger vortex structure whose size has exceeded the cross-sectional area of the train is produced at tail car. Figure 7 represents pressure contours of the head and tail cars. The pressure stagnation point of the head car is deviated from the train nose due to the effect of the crosswind.
4. CONCLUSION

Numerical simulation of aerodynamic characteristics of a high-speed train under different yaw angles is carried out in this paper, and calculation results are compared with the experimental data. The following conclusions are obtained:

(1) Through comparison with the experiment, the numerical simulation method based on the unstructured tetrahedral meshes and the pressure correction algorithm are feasible to carry out the research of aerodynamic characteristics of the train under the crosswind, especially below 15° yaw angle;

(2) The structure and size of the vortices in the leeward area of the train are continually evolving with the flow going from the head car to the tail car, and the flow field structure in the head car area is quite different from the tail car, which will affect the aerodynamic force;

(3) Drag, lift and other aerodynamic forces increase with the yaw angle, near 20° drag will reach the maximum.

REFERENCES


