Analysis on Aerodynamic Effect of Common Passenger Train and EMU Passing by Each Other under Crosswind

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ABSTRACT

The three-dimensional unsteady N-S equation and the $k$-$\varepsilon$ equation turbulence model were made to solve the aerodynamic performance of common passenger train passing by Electric Multiple Units (EMU) under crosswind based on the finite volume method and sliding mesh method. The results of full-scale train experimental method and numerical simulation method were compared. The results of numerical simulation show that when common passenger train and EMU pass by each other under crosswind, crosswind has great effect on the aerodynamic performance of trains. When there is no crosswind, the lateral force of the locomotive of common passenger train and the first car of EMU are the largest, 11.55 kN and 6.25 kN respectively. When there is crosswind and the wind speed reaches 40 m/s, the overturning moment of common passenger train and EMU are 87.9 kN·m and 239.9 kN·m, which means when trains pass by each other under strong wind, there are great security risks. When wind-break walls are set in line side, lateral forces of trains are significantly decreased.

Keywords: Common passenger train; EMU; Wind-break wall; Crosswind; Train-crossing; Aerodynamic effect.

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1. INTRODUCTION

High speed train can induce strong disturbance to the surrounding air. When two high speed trains are passing each other in open air, the disturbance will be aggravated, which would induce large transient pressure fluctuations [1]. There are various line environments around the running train, and when a train runs in the wind zone where is often subjected to strong wind attacks, the strong wind would make the characteristics of the flow field around the train more turbulent, which directly affect the aerodynamic performance of the train. In particular, a significant change in the flow field around the train and a rapid increase in the aerodynamic force of the train occur at two high-speed trains which are passing each other. Such events greatly increase the probability of derailment and rollover of trains.

Many researchers studied the flow around two high speed trains passing by each other at the same speed used numerical simulation or experiment techniques. Numerical simulations of the strain passing by on the double-track were carried out to study the effect of the train nose-shape, length and the existence of a tunnel on the crossing event [2]. RA MacNeill et al. described a set of experiments designed to gather pressure-time histories on a tall, large surface area double-stack container car as a high-speed train passes [3]. H.Q. Tian et al. studied the behaviors of trains passing each other at different speed levels and different line spacings, and the research proved that the amplitudes of pressure wave of trains passing each other are proportional to the train speed, and that the relationship between pressure wave and line spacing is negatively exponential [4]. Y Zhao et al. studied the influences of different open foundations (ground, embankment and bridge) on the dynamic behavior of trains passing each other [5]. Z Sun et al. investigated the aerodynamic characteristics and the running safety of trains passing by each other in the open air and in a tunnel [6].

Under strong winds, aerodynamic forces would have a great effect on the operation safety of high-speed trains with an increasing risk of overturning. Many scholars and institutes with developed railway traffic and transportation in their countries lots of research have been done. W. Khier et al. studied the flow structure around trains underside wind condition by simulation and obtained the aerodynamic performances of train running under side wind condition [7]. M Suzuki et al. evaluated the aerodynamic characteristics of the sleeping car, double deck passenger car and container car on bridges and embankments under cross winds by means of wind tunnel test [8]. Diedriches et al. studies on the crosswind stability of the trains under wind conditions mainly focus on high embankments [9]. F Cheli et al. studied the aerodynamic performance of the EMU250 train is by means of wind tunnel test and numerical simulation, and compared the aerodynamic characteristics of the original shape and the improved shape under cross wind [10]. K Ye et al. established the numerical calculation models of the high-speed train in the straight and different radius curve railway and calculated transverse forces (moments) acting on the three sections (first train, middle train and rear train) [11]. MA Rezvani et al. studied the
flow fields around a high speed train and summarized the numerical assessment of the aerodynamic characterization of a high speed train in different crosswinds which is found that the best agreement with experimental results corresponds to the $k-\varepsilon$ realizable turbulence model \cite{12}. M Suzuki et al. constructed full-scale models of a train/vehicle and a viaduct in a windy area, and measured wind characteristics and aerodynamic forces acting on the vehicle models by wind tunnel tests \cite{13}.

The aerodynamic characteristics of train under crosswind depend on not only the operation of train but also the infrastructure such as bridges, embankments and wind fences. Wind-break wall as a wind fence is increasingly installed on railway lines at wind zones, which is effective to reduce wind loads on vehicles and hence increase critical wind velocities of overturning \cite{14}. In China, wind-break walls have been built along Lanzhou-Xinjiang railway and high-speed railways which are easily affected by strong winds. In China, the Xinjiang railway lines are easily affected by monsoons and the wind direction is stable, which is almost perpendicular to railway line, hence, wind-break walls were built in the windward side of railway line \cite{15}. To ensure the running safety of common passenger train pass by EMU under strong crosswind, the aerodynamic characterization of trains should be evaluated.

2. THE VEHICLE MODEL

The geometry models include train model and wind-break wall. This paper studies the model of five-car marshalling of common passenger train and eight-car marshalling of EMU. The five-car marshalling train includes one locomotive car and four passenger cars. While the eight-car marshalling train consists of one head car, six middle cars and one tail car. According to the actual situation of test site, the model is composed of train model, ground and wind-break wall. Trains pass by each other in the ground, respectively, considering the wind-break wall or not, EMU is located in the windward side, common passenger train is located on the leeward side. The cross-sectional model of intersection model is shown in Fig.1.

![Figure 1. Cross-sectional model (unit: m).](image)
3. NUMERICAL MODEL

3.1 Computational method

When two trains are passing each other at the speed of 250 km/h and 160 km/h, the air flow around train is unsteady and turbulent in nature with high Reynolds number, which is much larger than the critical Reynolds number for the laminar and turbulent flow. Thus, the flow around trains are turbulent, and the three-dimensional Reynolds-averaged Navier-Stokes equations (RANS) combine with the eddy viscosity hypothesis are used to describe the flow field around the train and behind the wind-break wall.

In the current simulation, the pressure-based solver uses the SIMPLEC algorithm to introduce pressure into the continuity equation. A second-order upwind scheme is chosen for solving the Navier–Stokes equations. For the residual of continuity, the absolute criterion of convergence is set to $10^{-6}$ with over 2000 iterations. The time step is 0.005 s, which is sufficiently small to resolve the unsteadiness in the flow field.

3.2 Boundary Condition

The calculation zone is shown in Fig.2. The surface is defined with no-slip wall boundary condition, and the outlet is set to the pressure outlet boundary condition. The track bed, ground and wind-break wall are defined as the wall. The top of the field is set to the symmetry. To obtain a stable initial flow field, trains are kept stationary and crosswind is applied to the computational domain. Then, the train motion is induced after the initial flow field is fully developed in the computational domain. The sliding mesh method is used to implement the train motion relative to another train.

3.3 Computational Grid

In order to take into account the speed and accuracy of the solution, a simplified model is adopted without considering detailed features, such as pantographs, bogies and door handles. Since the geometry of train is complicated, a more adaptive non-
structured grid method is used for discretization. The sliding blocks and the mixed mesh approach are adopted. The count of mesh is about 22.5 millions. The mesh of the trains body surfaces are shown in Fig. 3.

4. VERIFICATION OF COMPUTATIONAL MODELS

To verify the calculation method used in the paper, the present model is applied to simulate the field observation of the full-scale train test. The aerodynamic pressure that is generated by trains running under 3.5m wind-break walls at the speed of 160 km/h under the crosswind of 12.9 m/s is measured. The pressure wave of the measuring point on the middle car surface attained from the simulation is compared to the experimental data, as shown in table I. \( P_{\text{max}} \) means the maximum pressure, \( P_{\text{min}} \) means the minimum pressure, \( \Delta P \) represents the pressure amplitude, and \( \Delta P = P_{\text{max}} - P_{\text{min}} \).

<table>
<thead>
<tr>
<th>Method</th>
<th>Pressure of intersecting side (Pa)</th>
<th>Pressure of non-intersecting side (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P_{\text{max}} )</td>
<td>( P_{\text{min}} )</td>
</tr>
<tr>
<td>Full-scale test</td>
<td>93.03</td>
<td>-195.45</td>
</tr>
<tr>
<td>Numerical simulation</td>
<td>93.89</td>
<td>-206.60</td>
</tr>
<tr>
<td>Relative error</td>
<td>0.92%</td>
<td>5.70%</td>
</tr>
</tbody>
</table>

By comparing the pressure wave of two models, it can be seen that the present pressure variation is in good agreement with the experimental result, and the deviation in peak values of two models are less than 10%. This indicates that the numerical calculation method is suitable to be applied to the study on aerodynamic effect caused by trains passing by each other.

5. RESULTS AND DISCUSSION

5.1 The Flow Structure

The high-speed train makes the flow around the train a strong disturbance, and this disturbance is exacerbated when two trains pass by each other. Fig. 4 shows the two-dimensional streamlines of different cross section when common passenger train passing by the head, middle and tail car of EMU under the 3.5m wind-break wall or not. When there is no wind-break wall, the two-dimensional streamlines are shown in Fig. a~c that is shown in Fig. 4, due to air directly act on the front of EMU, the surface would reduce the flow rate and increase the pressure, and the side wall to the roof at the transition due to changes in curvature, makes the airflow speed around
these position increased, resulting in a sharp reduction in pressure in this area, forming a negative pressure zone. Air flow between EMU and common passenger train quickly spread to the surrounding, forming a negative pressure zone too. The acceleration of air in the leeward side of common passenger train is accelerated by the train roof, which makes the airflow evacuated and forms a negative pressure zone. It can be seen that the pressure distribution is different due to the asymmetry of the flow field on both sides of the carriage, and the difference of pressure is easy to produce lateral forces. When two trains passing by each other, the compressed air easily flow from the bottom of common passenger train body to form a vortex, and the leeward side of the common passenger train is in a negative pressure environment. The two-dimensional streamlines, as shown in Fig. d−f that is shown in Fig. 4, due to the shielding effect of the crosswind, a positive pressure area is formed in the front of the wall, and the airflow after the wind-break wall is formed a large vortex. When two trains pass by each other in this condition, pressure distribution on both sides of trains become more evenly and pressure decrease when compared to no wind-break wall. The vortex formed in the leeward of common passenger train gradually away from the train surface, reducing its impact on the train body. It can be seen that the wind-break wall changes flow structure around trains, and has a great impact on the pressure of the surface of trains.

![Figure 4. Two-dimensional streamlines for different cross sections.](image)

5.2 The Effect of Crosswind Speed

Table II shows the peak values of lateral forces of common passenger train at 140 km/h pass by EMU at 250 km/h under 3.5m wind-break wall at different wind speeds.
From table II, we can see that when there is no crosswind, the lateral force of the locomotive of common passenger train and the head car of EMU are the largest, and the lateral forces of other cars are almost the same. When trains pass by each other in the crosswind environment, as for common passenger train, the peak value of positive lateral force of locomotive is larger than the negative value. As for EMU, due to the impact of the wind-break wall, lateral forces of two trains increase with the increase of the wind speed. The lateral force of common passenger train is affected by wind speed is smaller than that of EMU, mainly because EMU on the windward is against the crosswind. When the wind speed increases from 0 m/s to 40 m/s, the peak value of lateral force of tail car of common passenger train is increase by 66.03 kN than those without wind-break wall, while the peak value of the tail car of EMU increased by 107.74 kN, which is 12.3 times higher than that without wind. It can be seen that trains pass by each other in crosswind environment, the lateral forces increase sharply.

Fig. 5 is curves of overturning moment on common passenger train and EMU changed with different wind speeds. It can be seen that the overturning moment of the middle car is increasing rapidly with the increase of wind speed. When the wind speed is higher than 30 m/s, the head wave and stern wave do not change obviously, mainly because the wind becomes the main factor affecting the distribution of the flow field around trains. When the wind speed reaches 40 m/s, the overturning moment of common passenger train and EMU is 87.9 kN·m and 239.9 kN·m respectively. When the trains pass by each other under strong crosswind, there are great security risks.
5.3 Comparison of aerodynamic performance before and during passing

In order to evaluate the aerodynamic performance of trains before and during passing, as the common passenger train for an example, the lateral force of every carriage before and during passing is compared, as shown in table III.

<table>
<thead>
<tr>
<th>Vehicle number</th>
<th>Lateral force without breakwalls (kN)</th>
<th>Lateral force with breakwalls(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before passing</td>
<td>Maximal value before passing</td>
</tr>
<tr>
<td>1</td>
<td>53.5</td>
<td>90.9</td>
</tr>
<tr>
<td>2</td>
<td>45.8</td>
<td>65.2</td>
</tr>
<tr>
<td>3</td>
<td>40.5</td>
<td>54.6</td>
</tr>
<tr>
<td>4</td>
<td>37.9</td>
<td>50.4</td>
</tr>
<tr>
<td>5</td>
<td>36.4</td>
<td>49.6</td>
</tr>
</tbody>
</table>

We can see that the lateral force of the locomotive is the largest when there is no wind-break wall, because the pressure caused by head wave and the initial pressure caused by the crosswind are superposed. The peak value of lateral force of the locomotive and tail car during passing is increased by 1.7 times and 1.3 times than before passing, which means there is a certain security risk when they are passing by each other in the strong wind. When there is 3.5m wind-break wall, the lateral forces of common passenger train have decreased significantly, which indicates that the shielding effect of the wall is obvious, but the direction of the lateral force before passing is against the wind direction, which means the windproof capacity is excessive.

Fig. 6 is the histogram for the peak-to-peak value of lateral forces of trains passing each other with or without wind-break wall. As we can see that the peak-to-peak value of the head car is the biggest, and that of the middle cars is close. When there is 3.5m wind-break wall, they have been reduced compared to no wind-break wall, the aerodynamic performances of trains are significantly improved.
6. CONCLUSION

This research focused in studying the aerodynamic effect of trains passing by each other under crosswind. The numerical results were compared with the experiment data in order to validate the numerical procedure. Based on the analysis of the results, the following can be reported:

(1) When there is no wind-break wall, crosswind makes air flow on both sides of train asymmetry, which produces a lateral force. When there is 3.5m wind-break wall, it significantly changes the structure of the flow field around trains, and generates a negative pressure zone, and the pressure distribution on both sides of the train become more uniform compared to no wind-break wall.

(2) When the wind speed increases from 0 m/s to 40 m/s, the lateral forces of trains increase sharply, and the peak value of lateral force of tail car of common passenger train is increase by 66.03 kN than those without wind-break wall, while the peak value of the tail car of EMU increased by 107.74 kN, which is 12.3 times higher than that without wind. When wind speed reaches 40 m/s, the overturning moment of common passenger train and EMU are 87.9 kN·m and 239.9 kN·m, which means there are great security risks if trains pass by each other in the strong crosswind.

(3) When EMU and common passenger train pass by each other under crosswind, the peak value of lateral force is obviously larger than that of before passing. EMU and common passenger train pass by each other in strong crosswind environment without windbreak wall, which seriously affect the safety of trains.

REFERENCES