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Aerodynamic mechanisms of tornado-induced wind load on a high-speed train

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SUMMARY:
Tornado risks for high-speed railway systems in tornado-prone regions cannot be neglected. Based on previous experimental investigations of aerodynamic loads on a high-speed train exposed to tornado-like vortices, CFD simulations were conducted to interpret the aerodynamic mechanisms of wind load of the high-speed train passing through tornado-like vortices. The numerical results were verified through comparison of aerodynamic load coefficients to experimental results. It has been found that train motion will significantly change the tornado vortex structure surrounding the train and thus reduce the most unfavourable aerodynamic load coefficients. Other effects including different cars, line position relative to tornado center, as well as operation speed of the train have been also considered.

Keywords: tornado-like vortices, high-speed train, aerodynamic mechanism, CFD simulation

1. INTRODUCTION

According to statistics on tornado occurrences over the 50 years between 1961 and 2010, Jiangsu Province in eastern China experiences the largest number of severe tornadoes (EF2 or greater) in China and several coastal provinces such as Shanghai, Guangdong and Hainan are also tornado-prone areas in China (Xue et al., 2016). On the other hand, high-speed railway systems in China are mainly concentrated in these regions. In addition, the impact of a tornado strike on line-like structures such as railways, and power transmission lines may be more serious than on building structures. Recent wind induced accidents on trains caused by tornadoes have been reported (Matsui et al., 2009). Therefore, it is necessary to consider tornado effects on line-like infrastructures including high-speed trains in tornado-prone regions.

Although a great quantity of studies were performed to understand the running risk of high-speed trains in cross winds, there have been relatively few studies on aerodynamic load coefficients and their effects on high-speed trains under tornado flows through physical and numerical simulations. Baker and Sterling (2018) presents a novel methodology for calculating the risk of a train overturning accident due to tornadoes, with the aerodynamic load coefficients obtained in a large low turbulence wind tunnel. In this study, CFD simulations were conducted to interpret the aerodynamic mechanisms of wind load of the high-speed train passing through tornado-like vortices, which can be used for evaluations on tornado-induced risks of high-speed trains.

2. NUMERICAL SETTINGS

2.1. Computational domain and boundary condition

Based on the physical tornado simulator where wind loads on the train model were measured, a numerical tornado simulator (see Fig.1) is established and a moving train model is embedded in the simulator to realize the relative motion of the train and the tornado vortices. The blue boundary provides a downward and rotating inlet flow, and the red part at the top is the pressure outlet. The purple area is the moving grid section where the train is included.

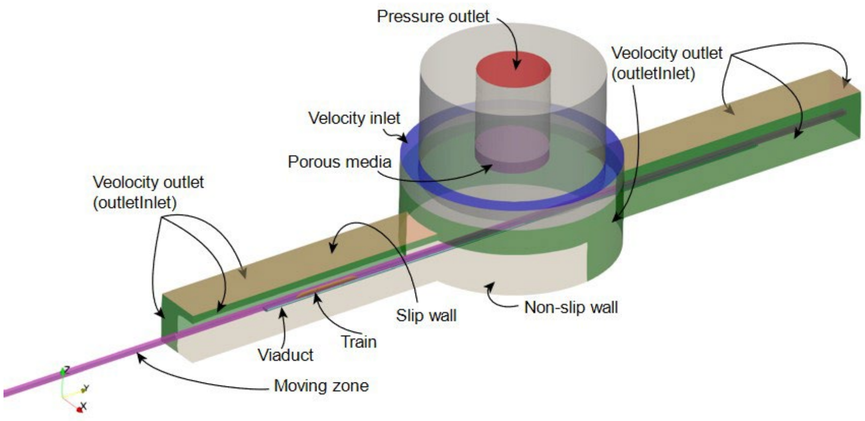

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Figure 1. Numerical model.

2.2. Grid meshing

As shown in Fig.2, the grid is divided into two regions, the moving and stationary regions. Real-time exchange of flow field data is accomplished by interpolation between the two regions. The height of the first grid after scaling is set to 0.16 mm, and it is extended by 3 layers with an expansion rate of 1.05 to ensure $y^+ < 5$.

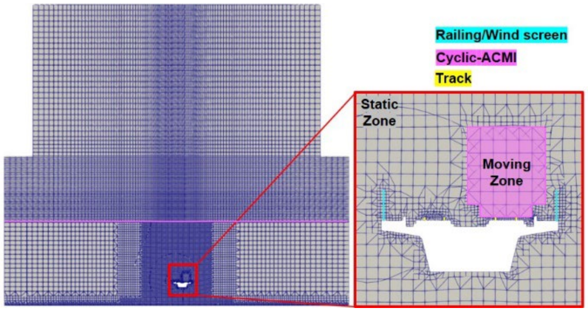

Figure 2. The grid.

3. AERODYNAMIC LOAD CHRACTERISTICS

Aerodynamic load coefficients on a stationary train under tornado vortices were first calculated and compared to experimental results with the tornado centre at the same place. The results in Fig. 3 includes overall drag and uplift force coefficients as well as overturning moment coefficients. It can be seen that the overall wind force and moment coefficients varied for different cars, which indicates that the tornado effect has obvious spatial local characteristics.

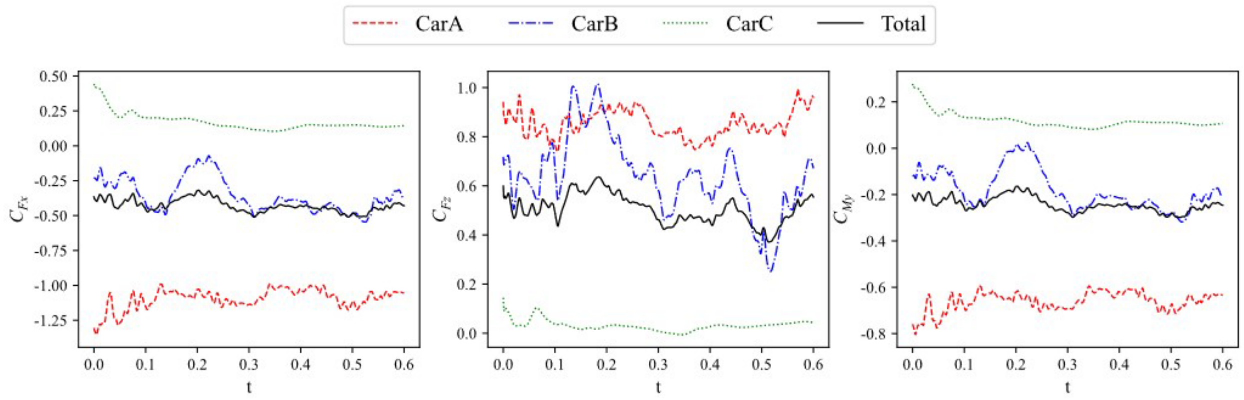

Figure 3. Aerodynamic load coefficients of three cars of the train.

Comparing the numerical simulation results of the three components of the most unfavourable overall wind force and moment coefficient with the results of the physical simulation conducted previously, the results of both can be found to be in good agreement, which verifies the numerical schemes for the aerodynamic load effects on the train under tornado-like vortices.

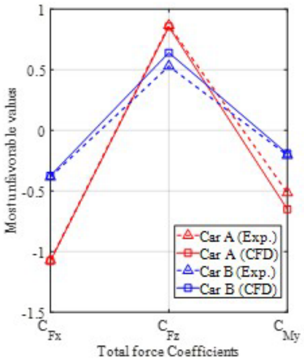

Figure 4. Comparison of numerical and experimental aerodynamic load coefficients.

4. AERODYNAMIC MECHANISMS

4.1. Effect of train motion

The overall aerodynamic load coefficients when the train is moving are compared in Table. 1 with those when it is stationary. For Case 1, the stationary train model is at the position corresponding to the most unfavourable overall aerodynamic load coefficients. For Case 2 and 3, the train model is moving when it pass through the same position as Case 1, and the position corresponding to the most unfavourable overall drag coefficients for all motion cases, respectively. Comparing Case 1 and 2, the magnitude of overall aerodynamic load coefficients of the moving train is smaller than that of the stationary train in the case of the most unfavourable position of the stationary train. Comparing Case 1 and 3, it is indicated that even the most unfavourable overall aerodynamic load coefficients of the moving train are all smaller than those of the stationary train.

Table 1. Comparison of most unfavourable aerodynamic load coefficients between stationary and moving train

Case	Train model	y/r_c	C_{Fx}	C_{Fz}	C_{My}
1	Stationary	2.16	−1.08	0.85	−0.65
2	Moving	2.16	−0.66	0.76	−0.38
3	Moving	1.41	−0.79	0.59	−0.48

The most obvious difference of the surrounding flow field between stationary and moving train model is in the wake of the train (see Region 1 in Fig.5). Due to the presence of the train wind, the original tornado vortex structure is turned into radial flow, which results in a weakening of the positive pressure on the windward side of car A. For leeward side, the train motion accelerates the radial flow in Region 2 and decelerate it in Region 3, which increase the magnitude of negative pressure in Region 2 and decrease it in Region 3. The superposition of the above two effects reduces the pressure difference between the windward and leeward sides of car A, thus making the drag coefficient of the moving train become smaller in magnitude.

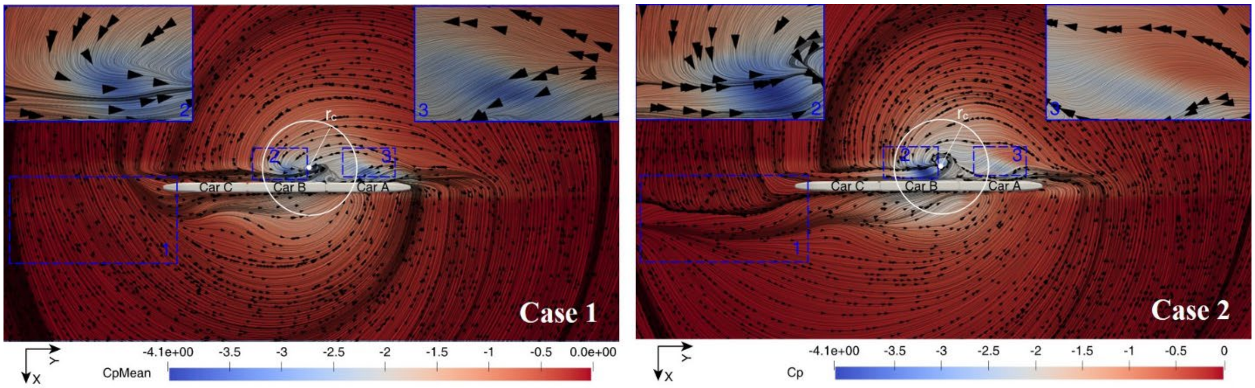

Figure 5. Comparison of flow field and pressure contour.

5. CONCLUSIONS

Based on experimental investigations of aerodynamic loads on a high-speed train exposed to tornado-like vortices, CFD simulations were conducted to interpret the aerodynamic mechanisms of wind load of the high-speed train passing through tornado-like vortices, such as the effect of train motion. Other effects including different cars, line position relative to tornado center, as well as operation speed of the train will be included in the full paper.

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