Aerodynamic Load Characteristics of High-Speed Train under Different Wind Load Models

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Abstract. In order to study the difference of unsteady aerodynamic loads of high-speed train under different wind load models, considering the assumption of uniform wind and the random characteristics of wind, the turbulent velocity field is generated by CDRFG method. A numerical model of cross-wind aerodynamics for high-speed trains was established by using STAR-CCM+, and solved by the IDDES method. The time history curve of fluctuating wind was transported into the computational domain as a function to calculate the computational fluid dynamics directly. The variation law and difference of aerodynamic load of high-speed train under two kinds of wind load models are obtained. With the increase of yaw angle, the maximum, average and standard deviation of aerodynamic load coefficient increase, and the coefficient fluctuation becomes more intense. The aerodynamic performance of the head car is the worst among the three cars. The PSD of aerodynamic load under stochastic wind is higher than that under uniform wind. With the increase of yaw angle, the corresponding PSD difference of aerodynamic load between stochastic wind and uniform wind increases, which indicates that the effect of pulsation is more obvious.

1. Introduction

With the rapid development of the national economy, railways have become an important part of the transport industry. High-speed and lightweight of the train will bring a series of new aerodynamic and dynamic deterioration problems, especially the safety of train operation under crosswind environment. Train derailment and overturning accidents caused by wind have occurred many times in the world, so it is necessary to study the crosswind operation safety of the high-speed train. Scholars have carried out extensive researches on the train aerodynamic characteristics under crosswind, but previous studies are mostly based on the assumption of uniform wind. However, natural wind has fluctuating characteristics, and the calculation and analysis based on uniform wind are quite different from the actual situation. Based on Von Karman spectrum, Cooper¹ proposed Cooper theory to calculate the aerodynamic load of fluctuating wind near trains. Baker² proposed a method for calculating the unsteady aerodynamic loads of trains under stochastic wind by combining numerical simulation with wind tunnel test. Cheli³ used wind tunnel test to study how the relevant aerodynamic load coefficients of trains were affected by the turbulence intensity of natural wind and the motion of trains, the numerical model of aerodynamic admittance function was given. In these studies, most of the aerodynamic loads of train under stochastic wind are calculated indirectly by the method of fluctuating wind speed spectrum combined with aerodynamic admittance function. The aerodynamic loads obtained by this method are inaccurate. Very
few people use stochastic wind field as the input condition in CFD flow field calculation to directly simulate the operation of high-speed trains under stochastic wind.

In the study, the CDRFG method based on Von Karman spectrum is used to simulate the stochastic wind. The motion of the train under crosswind with different sideslip angles (0-20 degrees) is simulated by numerical simulation. The unsteady aerodynamic load characteristics of trains under uniform and stochastic wind conditions are analyzed and compared.

2. The numerical simulation of fluctuating wind

Stochastic wind in the nature is considered to consist of two parts, the mean wind with a period of more than 10 minutes and the fluctuating wind with a period of about several seconds. The characteristics of fluctuating wind can be expressed by power spectral density (PSD) function. According to experience, Von Karman spectrum defined as Eq. (1) is more suitable for bridges, vehicles, etc. and it is also used in EN14067 standard. Von Karman spectrum is used in this paper.

$$S_u(\omega) = \frac{200f}{n(1+50f)^{5/3}}$$

(1)

In Eq. (1), $S_u(\omega)$ is the wind power spectrum, $u_*$ is the shear friction velocity, $u_* = \sqrt{\tau_0/\rho}$, $n$ is the frequency, $\tau_0$ is the shear force, and $f$ is the conversion frequency.

Based on Von Karman wind spectrum, the stochastic wind is generated by CDRFG method. Based on the turbulence synthesis method (RFG), Huang\[4\] proposed a CDRFG method to generate random fluctuating wind, which is used to generate turbulent velocity fields satisfying the target turbulence spectrum and spatial and temporal correlation. The basis of this method is to discretize the power spectrum of the velocity into some segments, and to generate the pulsating wind field in each segment using the improved original RFG method. This method allows the modeling of the spectrum with arbitrary distribution. The turbulent velocity field is generated by the Eq. (2).

$$u_i(x_j, t) = \sum_{m=1}^{M} \sum_{n=1}^{N} p_i^{mn} \cos(k_j^{mn}\bar{x}_j^m + 2\pi f_{n,m}t) + q_i^{mn} \sin(k_j^{mn}\bar{x}_j^m + 2\pi f_{n,m}t)$$

(2)

Where $u_i$ represents longitudinal, transverse and vertical velocities, for $i = 1, 2, 3$ respectively; $j = 1, 2$ and 3 represents x, y and z directions, respectively; $M$ is the number of spectral segments; $N$ is the number of random frequencies in each segment; $p_i^{mn}$ and $q_i^{mn}$ are parameters specific defined in reference [4]; $f_{n,m}$ is normal-distribution random number with zero mean and standard deviation $f_{m}$; $k_j^{mn}$ are coordinates of points with uniform distribution of unit radius on the sphere to maintain the condition of divergence-free; $\bar{x}_j^m$ is a non-dimensional position parameter generated by Eq. (3).

$$\bar{x}_j^m = \frac{x_j}{k_j^{mn}}$$

(3)
fluctuation in the lateral direction. Fig. 2 shows the wind speed time history curve generated by CDRFG method.

3. Aerodynamic simulation of the high-speed train under crosswind

3.1. Train model and computational domain

A 1/10-th scale high-speed train model with three carriages was adopted, which includes two head cars and one middle car. The model size is 7.8m (L) × 0.338m (W) × 0.37m (H) in scale. Figure 3 shows the simplified sketch of train geometric model.

![Figure 3. The diagram of train geometric model.](image)

The computational domain is a large hexahedron. The train model is placed in the domain as indicated in Fig. 4, where H equal to 4m. It can be seen that the domain boundary conditions of stochastic wind are slightly different from those of uniform wind. If the boundary conditions of stochastic wind are set same as uniform wind, it will cause periodic positive and negative oscillations of pressure, then the calculation won’t be convergent. So, it is necessary to change the cross-wind velocity inlet and pressure outlet on the side into periodic boundary conditions. The y-direction velocity of the stochastic wind field is realized by introducing a time-varying function into the boundary conditions, and it is transported to the computational domain at the entrance boundary conditions at a constant speed in the x-direction. Aerodynamic load coefficient is an important factor in describing the train aerodynamic characteristics. The aerodynamic coefficient \( c_F \) and aerodynamic moment coefficient \( c_M \) are defined as Eq. (4).

\[
\begin{align*}
  c_F &= F / (0.5 \rho A v_a^2) \\
  c_M &= M / (0.5 \rho h A v_a^2)
\end{align*}
\]  

(4)

Where, \( F \) is the aerodynamic force; \( M \) is the aerodynamic moment; \( \rho \) is air density; \( A \) is reference area; \( h \) is reference height; \( v_a \) is synthetic wind speed, the definition of \( v_a \) is shown in Fig. 5.

3.2. Numerical method

With the continuous development of computer software technology and hardware performance, the application of LES (large eddy simulation) method in turbulence simulation is increasing. However, LES requires fine computational grids and small time step, it does not satisfy \( y^+ \) in this study. The DES (detached eddy simulation) model combines the advantages of LES and RANS (reynolds averaged...
navier-stokes), it uses the RANS method to simulate the small-scale fluctuating motion near the wall, and uses LES method to simulate the detached vortices motion far from the surface. IDDES (improved delayed detached eddy simulation) method is developed on the basis of traditional DES model. IDDES can eliminate the shortcomings of the traditional DES model which is too sensitive to grid, and improve the simulation of turbulent boundary layer using RANS. Therefore, IDDES method is used in this study. In the IDDES method, a new sub-grid length is defined by Eq. (5). The main purpose of defining the length of sub-grid is to reduce the degree of sudden change, which will lead to a similar trend of eddy current viscosity, and may further destabilize the flow[5].

$$\Delta = \min\{\max\{C_w d_w, C_w h_{\max}, h_{wn}\}, h_{\max}\}$$  \hspace{1cm} (5)

Where, $d_w$ is the distance to the wall; $h_{wn}$ is the normal upward grid step; $C_w$ is the empirical constant, 0.15; $h_{\max}$ is the maximum grid spacing.

The specific equation definition of IDDES method can be found in reference [5]. In this study, a separated incompressible finite volume solver star-ccm+ is used for numerical simulation. In order to discretize the convection term, the hybrid numerical method is used to conversion between the finite central difference method in LES region and the second order difference method in URANS region. The second order difference scheme is used for turbulent flow and the second order implicit scheme is used for time integration.

3.3. Meshing strategy and calculation modes

The mesh generation has an important influence on the results of numerical simulation, so it is necessary to use reasonable mesh quantity and quality to obtain good results. STAR-CCM+ is used to divide grids. The grid is hexahedron, three encrypted areas are set on the grids. The grids of the section around the train model is shown in Figure 6. The number of grids is about 30 million. Considering the conditions of different yaw angles, the modes shown in Table 1 are selected for calculation due to the limitation of time and resources of numerical method DES.

![Figure 6. Mesh distribution.](image)

Table 1. Calculation modes.

| Synthetic velocity | Wind filed model       | Yaw angle     |
|-------------------|------------------------|---------------|
| 60m/s             | Uniform wind           | 5°, 10°, 15°, 20° |
|                   | Stochastic wind        | 5°, 10°, 15°, 20° |

4. Results and analysis

The characteristics of aerodynamic coefficients in time-domain and frequency-domain are compared and analysed.

4.1. Characteristics of train aerodynamic load in time domain

In order to compare the difference of train aerodynamic load under different wind field types, considering the average, maximum and standard deviation, the variation laws of lateral force, lift and overturning moment coefficients with the yaw angle are drawn, respectively, as shown in Fig. 7.

Taking the lateral force coefficient as an example to analyze, firstly the influence on the aerodynamic coefficients of different wind load models is compared. It can be seen that the difference of average
coefficients between different wind load models is very small, while the maximum coefficients under stochastic wind are larger than those under uniform wind, and the standard deviation under stochastic wind is larger too. Secondly, with the increase of the yaw angle, the maximum, average and standard deviation of the car aerodynamic coefficient under different wind load models are both increase. The increase of the standard deviation indicates that the fluctuation of the coefficient becomes more intense with the increase of the yaw angle. Then comparing the lateral force coefficients of the head car, the middle car and the tail car, it can be seen that the coefficients of the head car are the largest, and the tail car are the smallest. When the yaw angle is 20 degrees, the difference between the maximum and average values of the head car lateral force coefficients under stochastic wind conditions is about 38%, which shows that the lateral force coefficients of the head car varies greatly under the influence of the fluctuation characteristics of the wind.

4.2. Characteristics of train aerodynamic load in frequency domain

In order to analyze the periodic variation law of train aerodynamic load, the time domain signal of aerodynamic force under different working conditions is transformed by FFT, and the frequency domain information of unsteady aerodynamic load is obtained. The power spectral density (PSD) of aerodynamic loads at different yaw angles of head, middle and tail cars are shown in Fig. 8.

Taking the lateral force as an example, it can be seen that PSD under stochastic wind is higher than that under uniform wind, which is due to the low frequency of wind under turbulence, and the low frequency of aerodynamic load is the main component. As for the aerodynamic load PSD with the change of yaw angle, it can be seen that with the increase of angle from 5 to 20 degrees, the difference between the PSD of stochastic wind and uniform wind increases, which indicates that the pulse effect is more obvious. The spectrum characteristics of the head car, the middle car and the tail car are similar, but the difference between the PSD of stochastic wind and uniform wind is obvious at the same yaw angle. The difference of the head car is obviously larger than that of the middle car and the tail car, and the difference of the tail car is the smallest, indicating that the head car is the most affected by the fluctuation characteristics of stochastic wind, followed by the middle car. The PSD variation law of lift

Figure 7. Variation of coefficient with yaw angle.

Figure 8. Variation of coefficient with yaw angle.

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and overturning moment is similar to that of lateral force. Among which the lift force variation law is slightly different. The PSD difference between stochastic wind and uniform wind of head car is smaller than that of middle car and tail car, and the difference of tail car is the greatest.

![Figure 8. PSD of aerodynamic loads at different yaw angles.](image)

Figure 8. PSD of aerodynamic loads at different yaw angles.

5. Conclusion

1. The average aerodynamic load coefficients of the train under different wind fields are similar, while the maximum and standard deviations under stochastic wind are larger than those under uniform wind. With the increase of the yaw angle, the maximum, average and standard deviation of each coefficient increase, and the coefficient fluctuation becomes more intense.

2. In the frequency domain analysis of aerodynamic load, the PSD of aerodynamic load coefficient under stochastic wind is higher than that under uniform wind. With the increase of yaw angle, the difference of PSD between stochastic wind and uniform wind increases, which indicates that the effect of pulse is more obvious.

Acknowledgments

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References

[1] Cooper R K. (1984) Atmospheric turbulence with respect to moving ground vehicles[J]. Journal of wind Engineering and Industrial Aerodynamics, 17(2):215—238.

[2] Baker C J . (2010) The simulation of unsteady aerodynamic cross wind forces on trains[J]. Journal of Wind Engineering and Industrial Aerodynamics, 98:88-99.

[3] Tomasini G , Cheli F . (2013) Admittance function to evaluate aerodynamic loads on vehicles: Experimental data and numerical model[J]. Journal of Fluids and Structures, 38(Complete):92-106.

[4] Huang S H , Li Q S , Wu J R . A general inflow turbulence generator for large eddy simulation[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2010, 98(10-11):600-617.

[5] Shur M L, Spalart P R, Strelets M K, et al. (2008) A hybrid RANS-LES approach with
delayed-DES and wall-modelled LES capabilities[J]. International Journal of Heat & Fluid Flow, 29(6):1638-1649.