IOP Conf. Series: Materials Science and Engineering **397** (2018) 012142 doi:10.1088/1757-899X/397/1/012142

Study on the comfort of high-speed train drivers in a windy environment

Hongyu Zhang, Jun Mao, Yaodong Sun and Yanhong Xi

Beijing Jiaotong University, Beijing, 100044, China
E-mail: jmao@bjtu.edu.cn

Abstract. Conducting the study on the comfort of high-speed train drivers in a windy environment, this paper based on the logical sequence of "train aerodynamic characteristics - vehicle dynamic response - human biomechanical properties - human body comfort evaluation". Taking the domestic CRH3 high-speed train as the research object. Firstly, the aerodynamic loads acting on the car bodies of the train under different wind speeds and different vehicle speeds were calculated. Then considering the effect of the wheel-rail adhesion and the irregularity of the track line, establish a vibration transfer model of 'rail – wheelset – bogie – carriage - seat', the aerodynamic loads are loaded onto the train to calculate vehicle dynamics and train vibration response under different operating conditions, the vibration characteristics of carriages and seats are obtained. Subsequently, the seat-human vibration transfer model were established and the seat vibration response was introduced into the human dynamics model to calculate the vibration response of different body parts of the driver under different operating conditions. And on the basis which are mentioned above, we summarized the influence rule of wind speed and train speed on human vibration response, From the human body's own point of view, the main factors affecting comfort and the mechanism of action were analyzed. Finally, the comfort standard was integrated to evaluate the comfort of the driver.

1. Introduction

High-speed railway must not only guarantee the safety of operation, comfort is also the goal and direction of its development. It is common for high-speed trains to operate under wind conditions. Compared with the windless condition, the surface aerodynamic load and vehicle dynamics of the high-speed train are significantly changed when it is operated in a windy environment [1], which affects the ride comfort of the personnel [2]. High-speed train drivers are not only prone to fatigue, but also the front position of the high-speed train is the most obvious position of the vibration response of entire train. The comfort of driving involves safety risks. Therefore, the study of its ride comfort has important practical significance.

At present, there are many studies on the aerodynamic characteristics and its dynamic characteristics of high-speed trains under wind conditions. Mao Jun et al. studied the effect of crosswind on the operational stability of high-speed trains by using a combination of flow numerical simulation and multi-body dynamic simulation. Zhang E used ADAMS/Life MOD software to build a human-vehicle system biomechanical simulation model to explore the human ride comfort. However, these studies mainly focused on the characteristics of high-speed trains themselves, and did not link these vehicle responses with human riding high-speed trains [3]. Moreover, the research on the ride comfort is mostly limited to the simplified human body model and the automotive field. There is relatively little research on the riding comfort of high-speed trains, and there is a lack of research on the ride comfort of high-speed trains in windy environments [4].

IOP Conf. Series: Materials Science and Engineering **397** (2018) 012142 doi:10.1088/1757-899X/397/1/012142

2. Variation of Aerodynamic Loads of High-speed Train in Wind Environment

Considering the research content and computational efficiency comprehensively, crosswind speeds of 10m/s, 15m/s, 20m/s, train speeds of 200km/h, 300km/h, 350km/h, and 400km/h are designed. A total of 12 sets of calculation conditions. In the numerical simulation of vehicle aerodynamic load calculation, considering the complexity of the model and the large amount of grids, the fluid dynamics software Star-CD/CCM + was used.

2.1. Numerical Simulation Model of Cross-Wind Aerodynamic Characteristics of High-speed Trains

Due to the same cross-sectional shape of the mid-body, three vehicles model can reflect the aerodynamic load characteristics of high-speed trains, which consists of head train, middle train and tail train. The details of the train's pantographs and bogies are simplified, and both the head train and the tail train are streamlined. Trim grids are used, and areas around the train are encrypted, the wall function method is used in the near wall area. After verification of the number of grids is irrelevant, the total number of grids to be calculated is about 2 million.

Figure 1. High speed train model

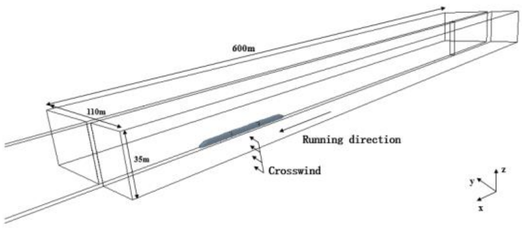

Figure 2. Calculation domain

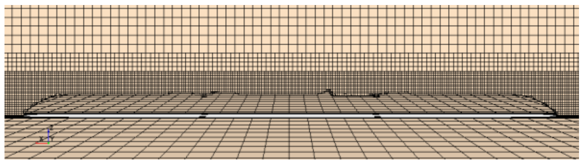

Figure 3. Meshing

The resistance, horizontal force, lift force and the aerodynamic load value of capsizing moment, pitch moment, cornering moment of high-speed railway in each operation condition can be calculated via numerical simulation.

2.2. Numerical Simulation Results and Analysis

Figure 4 shows the pressure cloud and speed vector diagrams of high-speed trains at different wind speeds. The train runs from left to right, the crosswind acts on the train from the left side of the train's running direction. With the purpose of observed the flow field around the high-speed train more clearly, the pressure threshold was set to -500 Pa - 500 Pa, and the speed threshold was set to 0 - 30 m/s.

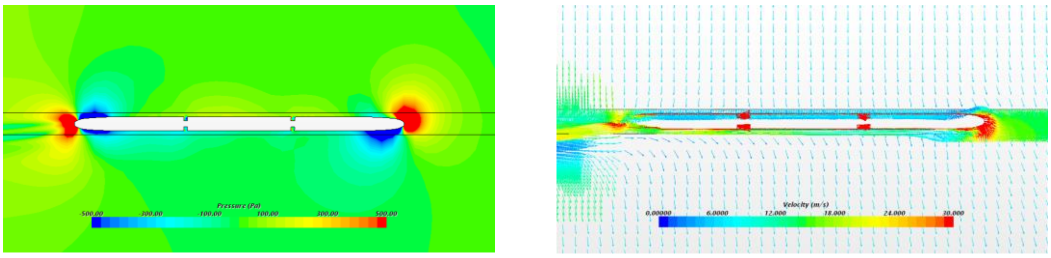

Figure 4. Pressure and Velocity vector under different conditions

In the absence of crosswind, the pressure and velocity distribution around high-speed train are approximately symmetrical about the train longitudinal direction; When crosswind effects, due to the combined action of crosswind and train wind, synthesis of airflow and the train direction formed a

IOP Conf. Series: Materials Science and Engineering **397** (2018) 012142 doi:10.1088/1757-899X/397/1/012142

certain yaw angle, and with the increase of the crosswind speed and the train speed, the maximum aerodynamic pressure and velocity in the flow field are both increased.

The action point of aerodynamic force is the volume centre of the vehicle. Partial aerodynamic load calculation results of high-speed head train under different wind speeds and different vehicle speeds are showed in the following table, as the additional aerodynamic loads in the next dynamic simulation.

Table 1. Pneumatic load on High-speed train

Train Speed (km/h)	Crosswind Speed 10m/s					
	F_x(kN)	F_y(kN)	F_z(kN)	M_x(kN m)	M_y(kN m)	M_z(kN m)
300	-8.97	17.23	-3.21	-5.53	-100.5	109.1
350	-12.21	19.37	-2.43	-6.42	-134.5	126.0
Train Speed (km/h)	Crosswind Speed 20m/s					
	F_x(kN)	F_y(kN)	F_z(kN)	M_x(kN m)	M_y(kN m)	M_z(kN m)
300	-10.49	42.63	-20.13	-12.29	-161.3	213.9
350	-14.01	48.13	-18.27	-13.98	-199.5	252.4

3. Numerical Simulation of Vibration Characteristics of High-Speed Train

After obtaining the aerodynamic loads of high-speed trains under different operating conditions, it is used as the input function of the vehicle body, considering wheel-rail contact and track irregularity, the dynamic model of the high-speed train was established by Simpack software to simulate the motion characteristics of high-speed train.

3.1. Dynamic Simulation Model of Vehicle Body and Wheel-Rail

Take three sections of vehicle marshalling model as research object as well. The physical model mainly includes vehicle body and bogie structure, wheel-rail contact model and track line, etc [6]. The Simpack model of each vehicle is the combined structure of body - bogie - wheel pairs. The selection of wheel and rail type conforms to the actual "S1002G" tread and the standard 60kg/m rail. Kalker's simplified nonlinear theory is used to calculate the creep force and normal force between wheels and rails. The German track spectrum was used to simulate the irregularities of the line. The numerical simulation results of aerodynamic loads are loaded into the dynamic model in the form of a time excitation function. The Simpack model of the three-section vehicle marshalling is shown in the fig 5.

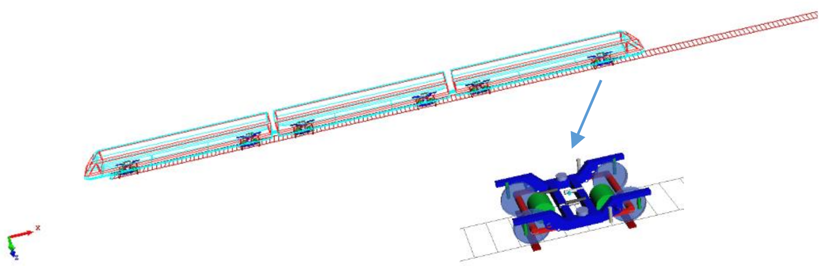

Figure 5. Simpack model of High-speed train and Bogie

3.2. Numerical Simulation Results and Analysis

Figure 6 shows the maximum value of the lateral (y-direction) acceleration and the vertical (z-direction) acceleration of the head vehicle at different train speeds when the crosswind speed is constant (15m/s). Figure 7 shows the lateral displacement curve of the vehicle body during a certain speed (350 km/h) with no cross-wind action and 15 m/s cross-wind loading.

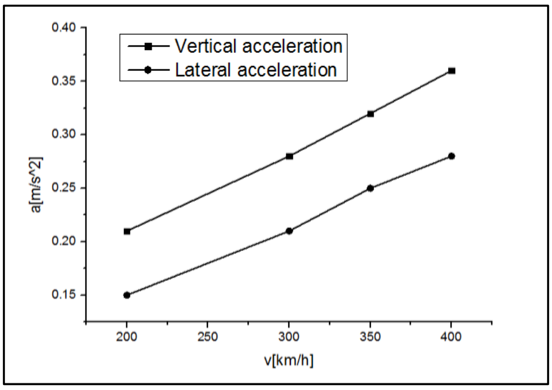

Figure 6. Comparison of Lateral and Vertical Acceleration of Headstock at Different Speeds

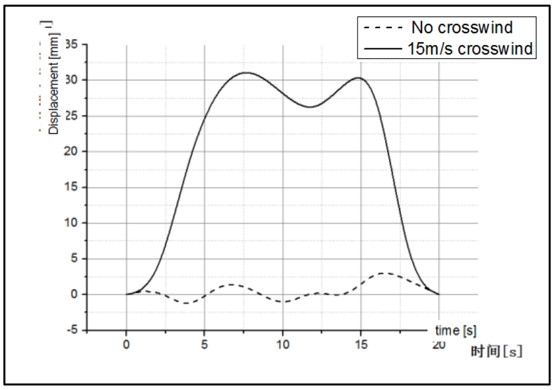

Figure 7. Comparison of lateral displacement of head carriage with or without cross wind

When the crosswind speed is constant, as the speed of the train increases, both the lateral acceleration and the vertical acceleration of the head vehicle tend to increase linearly. And the vertical acceleration of the vehicle body is always greater than the lateral acceleration. Under cross wind, the lateral displacement of the vehicle body is obviously increased compared with that without cross wind.

4. Numerical Simulation of Vibration Characteristics of High-speed Train Drivers

Hyperwoks software was used to build a seat - body model. Taking the vibration response of the vehicle body as an incentive function and input that incentive function to the seat which connects to the car body. Finally, the vibration response parameters of each part of the driver's body are obtained.

4.1. Seat-Human System Numerical Model

The model mainly includes four parts: human structure, seat cushions, the rigid body part of seat and floor. The human structure includes head, neck, trunk, limbs and feet and so on, it also defines the materials and properties of each part [7]. At the same time, the seat deformation caused by the contact between human body and cushion are pre-simulated. The vibration excitation is transferred to seat frame through the floor of vehicle body, and then caused the vibration response of human body that aroused by cushion and the feet in contact with the floor. The number of grids of the system model is about 700,000.

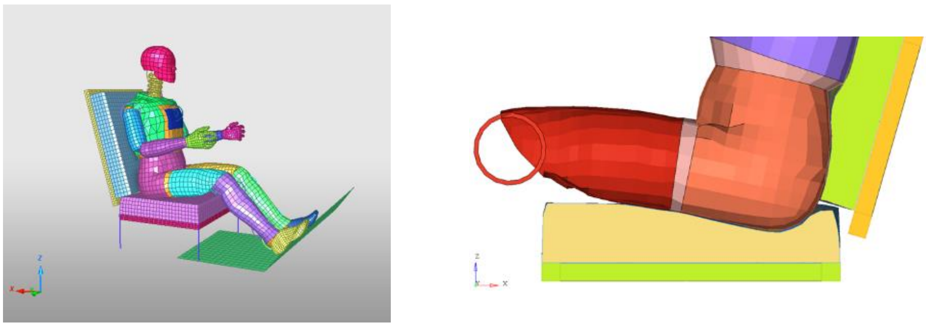

Figure 8. Seat-Human Model and Seat Deformation

4.2. Numerical Simulation Results and Analysis

Figure 9 is a cloud diagram of human body vibration acceleration. The driver's head and hand reach the maximum vibration acceleration, torso part close to maximum acceleration. The study mainly focused on the acceleration response of the torso and the head.

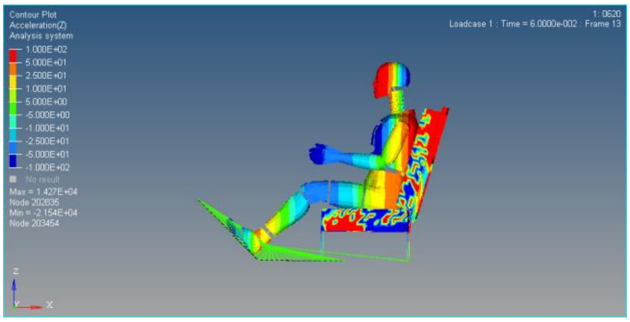

Figure 9. Head acceleration reaches maximum

The maximum value of the effective value of lateral vibration acceleration of the driver's human head is about 0.6 m/s^2, and its value is larger than that of the trunk. A similar conclusion can be reached by comparing the results of vertical acceleration.

Figure 10 and Figure 11 show the comparison of the acceleration curves of the human body and vehicle body at different vehicle speeds.

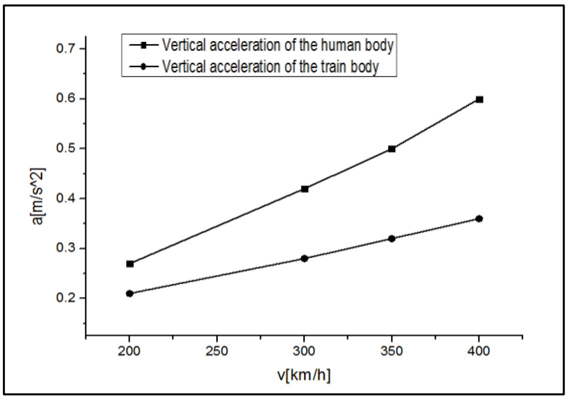

Figure 10. Comparison of Vertical Acceleration between Vehicle Body and Human Body

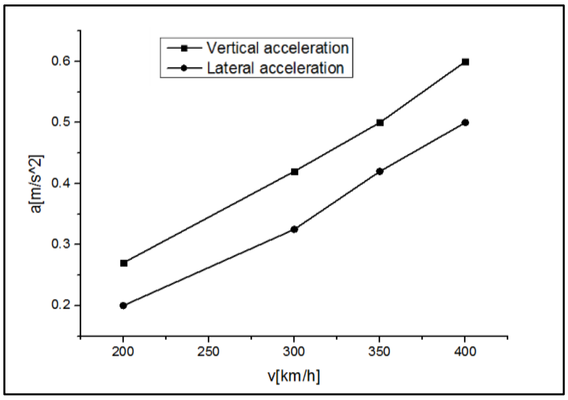

Figure 11. Comparison of Lateral and Vertical Acceleration of Human Body

5. Comfort Evaluation

The human body's vibration-related comfort is the result of the combined effects of vibration acceleration, vibration frequency and the mode and time of vibration [8]. In terms of vibration frequency, low-frequency vibration is a major factor in human comfort. In a normal gravity environment, the human body has the greatest impact on the rate of vibration energy and physiological effects in the frequency range of 4-8 Hz, called the first resonance zone of the human body. In terms of vibration acceleration, in general, when the vibration acceleration increases, the comfort of the human body will deteriorate [9].

In the standard ISO2631-1:1997 and GB/T13441.1, an approximate method for evaluating human comfort is given, that is, the RMS value of total weighted acceleration of whole body vibration is used to evaluate human comfort, The formula is as follows [10][11]:

$$a_\omega = \left[(1.4a_{xw})^2 + (1.4a_{yw})^2 + (a_{zw})^2 \right]^{1/2} \quad (1)$$

After algebraic operation, the RMS value of the total weighted acceleration of the whole body vibration in 20s varies with the speed of the train:

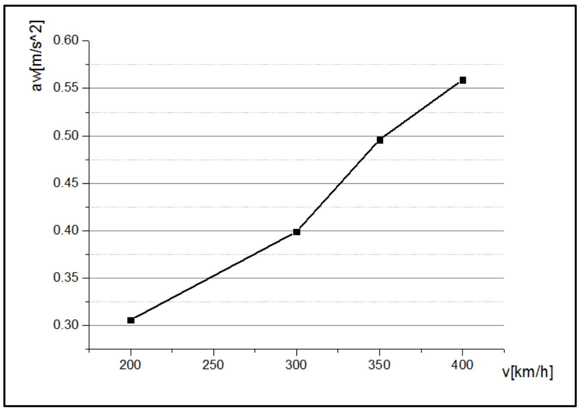

Figure 12. Weighted acceleration RMS of human body at different speeds

According to the evaluation criteria, the corresponding comfort responses at the vehicle speeds of 200 km/h, 300 km/h, 350 km/h, and 400 km/h were 'very comfortable', 'comfortable', 'comfortable' and 'somewhat uncomfortable'.

The lateral displacement of train will increase obviously due to crosswind effect, which leads to the change of vibrational frequency. Fig 13 shows the time course curve comparison of the horizontal (y direction) vibration frequency of human body when with the effect of 15m/s crosswind or without the crosswind effect.

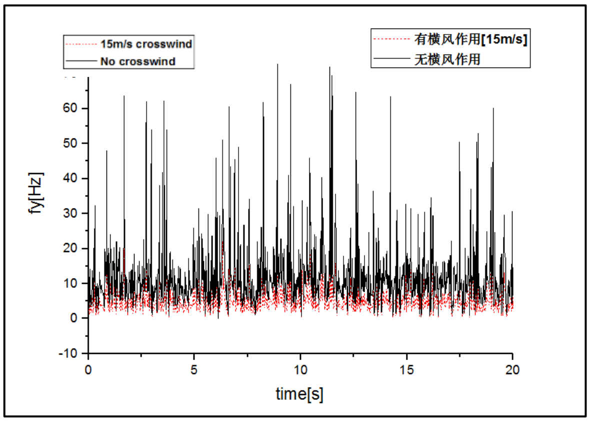

Figure 13. Comparison of transverse vibration frequency of human body with or without cross wind

In the presence of transverse wind, the overall lateral vibration frequency of the human body is smaller than that of the lateral vibration frequency without cross wind, and its value is closer to the first resonance zone of the human body. In this case, the physiological effect of human vibration is likely to be increased, and the ride comfort is adversely affected.

6. Conclusion

1) When running in the windy environment, the surface aerodynamic load and vehicle dynamic characteristics of high-speed railway are much different compared with no wind conditions, which result in the changes in movement characteristics and ultimately affect the ride comfort.

2) When the cross-wind speed is constant, the accelerations of the driver's body increase with the increase of the vehicle speed, and they are greater than those of the vehicle body under the same working conditions, indicating that the acceleration of the vehicle body has an increasing effect after being transmitted to the human body.

3) In the two main evaluation aspects of driver comfort, the change of vehicle speed has a greater influence on the RMS value of total weighted acceleration of whole body vibration, and its value

increases with the increase of vehicle speed, thus reducing comfort, while the change in wind speed has little effect on it. Crosswind will significantly increase the lateral displacement of human vibration, thus reduces the frequency of lateral vibration of human body and makes it closer to the first resonance zone of human body and causes bad effects to comfort.

Acknowledgment

The study was supported by the National Program on Key Basic Research Project of China(2016YFC0802206), Natural Science Foundation of China (Grant No. 51308040 and 51578061), the Fundamental Research Funds for the Central Universities (2017JBM095).

Reference

[1] Research on Aerodynamic Characteristics and Operational Safety of High - Speed Trains under Crosswind [D]. Beijing Jiaotong University, 2012.
[2] Research on Evaluation Method of Generalized Comfort of High-speed Train Based on Simulation Test Bench [D]. Southwest Jiaotong University, 2014.
[3] Wagner J, Liu X. An active vibration isolation system for vehicle seats [J]. SAE Paper, 2000, 1: 7 - 18.
[4] Noureddine A, Eskandarian A, Digges K. Computer modeling and validation of a hybrid III dummy for crashworthiness simulation [J]. Mathematical and Computer Modeling, 2002, 35: 885 - 893.
[5] Krajnovic, Sinisa. Optimization of aerodynamic properties of high-speed trains with CFD and response surface models. Proceedings of the Aerodynamics of Heavy Vehicles II: Trucks Buses and Trains, Lake Tahoe, USA, August 26 - 31 2007.
[6] Vehicle-Track Coupling Dynamics [M]. Beijing: China Railway Publishing House, 1996.
[7] China's 50th percentile male human body finite element model [4]. Automotive Technology, 2017 (24): 120 - 122.
[8] Wang H Y, Wang X M, Dang J W. An optimal method of comfort evaluation rules based on incomplete information system for high-speed railway [J]. Automation & Instrumentation, 2012, 192(1): 87-104.
[9] Liang C C, Chiang C E. A study on biodynamic models of seated human subjects exposed to vertical vibration [J]. International Journal of Industrial Ergonomics, 2006, 36(10): 869 - 890.
[10] ISO 2631- 1:1997, Mechanical vibration and shock-Evaluation of human exposure to whole body vibration-Part 1: General requirements.
[11] GB/T 13442:1992 reduced comfort boundary and evaluation criteria for human exposure to whole-body vibration. In Chinese.
[12] Study on Cross-wind Operation Stability of High-speed Trains Based on Flow Simulation and Dynamics Simulation [J]. Journal of Beijing Jiaotong University, 2011, 35(01): 44 - 48 + 53.