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Impacts of wind shielding effects of bridge tower on railway vehicle running performance

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Abstract. When railway vehicles run by towers of long span bridges, the railway vehicles might experience a sudden load-off and load-on phenomenon in crosswind conditions. To ensure the running safety of the railway vehicles and the running comfort of the passengers, some studies were carried out to investigate the impacts of sudden changes of aerodynamic loads on moving railway vehicles. In the present study, the aerodynamic coefficients which were measured in wind tunnel tests using a moving train model are converted into the aerodynamic coefficients in the actual scale. The three-component aerodynamic loads are calculated based on the aerodynamic coefficients with consideration of the vehicle movement. A three-dimensional railway vehicle model is set up using the multibody dynamic theory, and the aerodynamic loads are treated as the inputs of excitation varied with time for kinetic simulations of the railway vehicle. Thus the dynamic responses of the railway vehicle passing by the bridge tower can be obtained from the kinetic simulations in the time domain. The effects of the mean wind speeds and the rail track positions on the running performance of the railway vehicle are discussed. The three-component aerodynamic loads on the railway vehicle are found to experience significant sudden changes when the vehicle passes by the bridge tower. Correspondingly, such sudden changes of aerodynamic loads have a large impact on the dynamic performance of the running railway vehicle. The dynamic responses of the railway vehicle have great fluctuations and significant sudden changes, which is adverse to the running safety and comfort of the railway vehicle passing by the bridge tower in crosswind conditions.

Keywords: wind shielding effects of bridge tower; sudden changes of aerodynamic loads; crosswind condition; railway vehicle; running performance; multibody dynamic theory

1. Introduction

With the development of new light and high-strength materials, many super long-span bridges have been designed or being designed to cross straits and connect islands in coastal regions. The

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span length of some strait-crossing bridges is expected to reach the range of 2000 m ~ 5000 m (Astiz 1998), such as the planned Messina Strait Bridge with a main span of 3300m (Brown 1996), the advanced designs for the Gibraltar bridge with an unprecedented span length of 5000m (Astiz 1998). To support such long span length, the dimension of the bridge towers has been increased accordingly and could reach to tens of meters in the longitudinal direction. Meanwhile, the wind speed at the height of the bridge deck is considerably high since long-span bridges are often located near large water bodies of rivers, lakes or ocean bays or across valleys in great mountains. Some serious traffic accidents may occur on the long-span bridge exposed to moderate or strong winds (Wu and Chen 2011, Guo *et al.* 2013). Particularly, the wind shielding effects of the bridge tower could result in a serious aerodynamic problem for running vehicles and could affect the running safety and comfort for railway vehicles or highway vehicles.

When railway vehicles or highway vehicles pass by a bridge tower at a high speed under crosswind action, wind loads acting on the vehicles decrease suddenly due to the wind shielding effects of the bridge tower and then increase rapidly back to the normal after the vehicles have passed by the bridge tower. As a result, the vehicles passing by the bridge tower will experience a sudden load-off and load-on phenomenon in crosswind conditions. The sudden changes of wind loads might affect the running safety of vehicles and the comfort of passengers, and such changes in loadings could be significant especially when wind speed and/or vehicle speed are high. The dramatic changes in wind loads might induce critical traffic accidents, including overturning or derailment for railway vehicles, and undesired lane changes or rollover for highway vehicles.

Some studies have been conducted to investigate the sudden changes of aerodynamic loads acting on vehicles when high-sided road vehicles pass by the wake of a bridge tower in high crosswind conditions (Baker 1998, Charuvisit and Kimura 2004, Charuvisit *et al.* 2004, Cheli *et al*. 2006). Rocchi *et al*. (2012) used an experimental-numerical approach to investigate the sudden changes of aerodynamic loads acting on a high-sided vehicle. However, the aerodynamic loads were calculated by combining the wind tunnel test (using a static vehicle model under steady state condition) with a quasi-steady force distribution approach (Charuvisit *et al*. 2004). Aiming at the cases with and without localized wind barriers near a bridge tower, Argentini *et al*. (2011) conducted wind tunnel tests (using a static vehicle model) to measure the aerodynamic loads and the surface pressure distribution on a high-sided vehicle passing by the wake of a bluff tower. Li *et al*. (2010) simulated the wind field above the bridge deck nearby the towers of a long-span suspension bridge with the numerical simulation method, and measured the aerodynamic coefficients of the railway vehicles and bridge deck by wind tunnel tests (static vehicle model).

Among the aforementioned studies on the sudden changes of aerodynamic loads on vehicles from the wind shielding effects of bridge tower, most of them focused on road vehicles and the effects of vehicle movement were not considered. Charuvisit and Kimura (2004) pointed out that the vehicle movement should be considered in the analysis of sudden changes of aerodynamic loads on vehicles due to the wind shielding effects of bridge tower. Because the vehicle motion could modify the steady state of aerodynamic conditions, an asymmetry distribution in the variation of the aerodynamic loads will be introduced when the vehicle approaches or leaves the wake of bridge tower. Li *et al*. (2013) simulated the process of a moving train model passing by a bridge tower with a developed testing system and measured the sudden changes in the aerodynamic loads acting on the middle vehicle of the train model by wind tunnel tests, which provided a foundation for studying the impacts of the wind shielding effects of bridge tower on the running safety and comfort of railway vehicles in crosswind conditions. However, the impacts of wind shielding effects of bridge tower on the running railway vehicles have not been carefully investigated.

In the present study, the aerodynamic coefficients measured in wind tunnel tests using a moving train model (Li *et al*. 2013) are converted into the aerodynamic coefficients in the actual scale. A three-dimensional railway vehicle model is set up with the multibody dynamic theory. The aerodynamic loads acting on the prototype railway vehicle are calculated based on the aerodynamic coefficients with consideration of the vehicle movement and treated as the inputs of excitation varied with time for kinetic simulation in the Simpack Rail environment. Thus the dynamic responses of the railway vehicle passing by the bridge tower can be obtained from the kinetic simulations in the time domain. The impacts of sudden changes of aerodynamic loads on the running safety and comfort of the railway vehicle passing by the bridge tower will be discussed, addressing the effects of mean wind speeds and rail track positions on the running performance of the railway vehicle in crosswind conditions.

2. Aerodynamic characteristics of railway vehicle passing by bridge tower

2.1 Testing system in wind tunnel test

Fig. 1 shows the wind tunnel testing system with a moving train model (Li *et al*. 2013). Both of the train model and the bridge model are scaled down at a ratio of 1:45. The train model consists of three individual parts, namely, the front vehicle, the middle vehicle, and the end vehicle. The length of each vehicle model is 0.5 m and the entire train model is shown in Fig. 2 (Li *et al*. 2013). In the wind tunnel tests, only the aerodynamic loads acting on the middle vehicle of the train model are measured, whereas the front and the end vehicles of the train model are provided as the aerodynamic transition sections. Consequently, the aerodynamic loads acting on the middle vehicle are relatively stable since the influence of the 3D ambient flow on the middle vehicle is weakened by the two ends of the train model. Hereinafter, the aerodynamic coefficients and the corresponding aerodynamic loads of the railway vehicle are specifically referred to those of the middle vehicle.

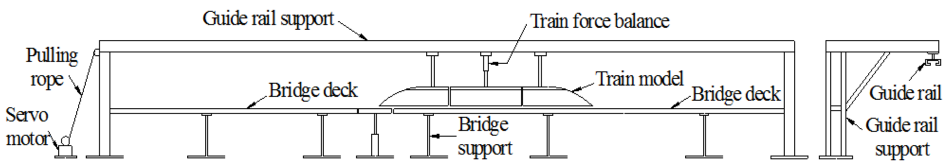


Fig. 1 Schematic diagram of wind tunnel test rig with a moving train model (Li *et al*. 2013)

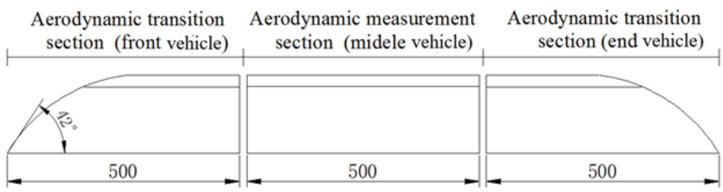


Fig. 2 Train model with three individual railway vehicles (Units: mm) (Li *et al*. 2013)

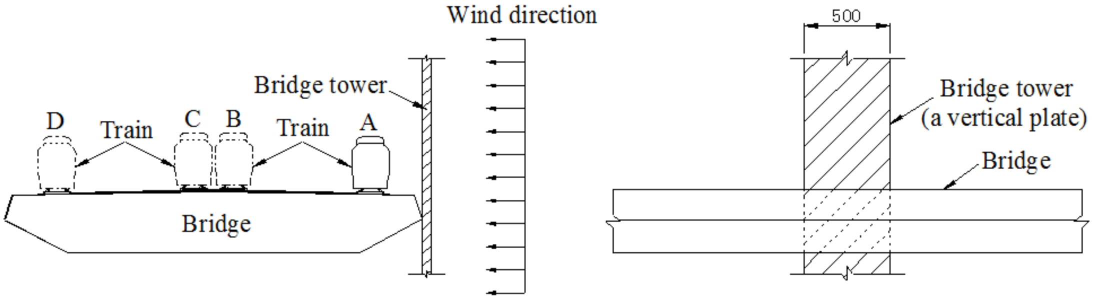


Fig. 3 Rail track position and bridge tower model (Units: mm) (Li *et al*. 2013)

In order to discuss the effects of different rail tracks on the aerodynamic characteristics of the railway vehicle passing by the bridge tower, four rail tracks named A, B, C, and D are set on the bridge model along the wind speed direction, as shown in Fig. 3 (Li *et al*. 2013). The train model can move along these rail tracks smoothly. The bridge tower is simulated with a vertical plate with a width of 0.5 m. The plate is installed on the windward side of the bridge model to simulate the wind shielding effects caused by the bridge tower, as shown in Fig. 3. Considering the total number of test cases and the associated test costs, each test case is repeated five times. The aerodynamic loads acting on the middle vehicle model can be obtained from the force balance. The signal processing method for the aerodynamic coefficients can be referred to the literature (Li *et al*. 2013).

2.2 Aerodynamic coefficients

In the present study, the three-component aerodynamic coefficients of the railway vehicle are defined as Eqs. (1)-(3)

$$C_H = F_H / \left(0.5 \rho \bar{U}^2 HL\right) \tag{1}$$

$$C_v = F_v / \left(0.5 \rho \bar{U}^2 BL\right) \tag{2}$$

$$C_M = M / \left(0.5 \rho \bar{U}^2 B^2 L\right) \tag{3}$$

where C_H, C_v and C_M represent the aerodynamic coefficients of drag force, lift force and rolling moment, respectively; ρ is the air density with the value of 1.225 kg/m^3; $\bar{U}$ is the mean wind speed; *H*, *B* and *L* are the height, width and length of the railway vehicle, respectively; F_H, F_v and *M* represent the drag force, lift force and rolling moment, respectively, and the positive directions of these aerodynamic forces and moment are shown in Fig. 4.

2.3 Variation of aerodynamic characteristics

In order to investigate the variation of the aerodynamic loads acting on the railway vehicle, a series of wind tunnel tests with mean wind speeds of 6 m/s, 8 m/s and 10 m/s were carried out, where the train model moved along the rail track A (closer to the bridge tower) and the rail track D (farther away from the bridge tower) at a speed of 8 m/s, respectively. The aerodynamic coefficients of the middle vehicle are shown in Fig. 5, where the train model moves along the rail track A at different mean wind speeds. The aerodynamic coefficients are found to decrease suddenly due to the wind shielding effects of the bridge tower and then increase rapidly after the train model has passed by the bridge tower. As a result, the railway vehicle experiences the sudden changes of wind loads during the process of passing by the bridge tower. The variation trends of the aerodynamic coefficients are similar to each other at different mean wind speeds. The range corresponding to the width of the bridge tower is from 6.75 m to 7.25 m (0.5 m in width). It should be noted that the average sudden-change region of the aerodynamic coefficients is from 4.5 m to 9.0 m, which is larger than the width of the bridge tower. This indicates that the vehicle-induced wind and the complex wind-structure interaction near the bridge tower can lengthen the sudden-change region which is caused by the wind shielding effects of the bridge tower. In addition, as shown in Fig. 5(a), the sudden change of the drag coefficient has an obvious weakening trend when the mean wind speed changes from 6 m/s to 8 m/s. However, the sudden-change extent of the drag coefficient can be found similar to each other when the mean wind speed increases from 8 m/s to 10 m/s. When the train model has not arrived in the sudden-change region affected by the bridge tower, the aerodynamic coefficients of drag force and rolling moment decrease with the increase of the mean wind speed as shown in Figs. 5 (a) and 5(c). This may be related to the aerodynamic interference of the vehicle-bridge system and the Reynolds effect. In addition, the flow separation from the front vehicle model during the process of train acceleration could lead to the instability of the flow field at the top of the train model. As shown in Fig. 5(b), the lift coefficients have large fluctuations, which could be related to the unstable airflow at the top of the train model.

Fig. 6 shows the aerodynamic coefficients of the middle vehicle moving along the rail track A and the rail track D at the mean wind speed of 10m/s and the vehicle speed of 8 m/s. As shown in the figure that the variation trends of the aerodynamic coefficients are similar to each other when the train model moves along different rail tracks. However, when the train model moves along the rail track A, the aerodynamic coefficients of drag force and lift force are larger than those of the train model moving along the rail track D, as shown in Figs. 6(a) and 6(b). In addition, when the train model moves along the rail track A, the sudden-change region of the aerodynamic coefficients has a wider width. It indicates that the aerodynamic loads acting on the middle vehicle have a more dramatic change when the train model moves along the rail track D.

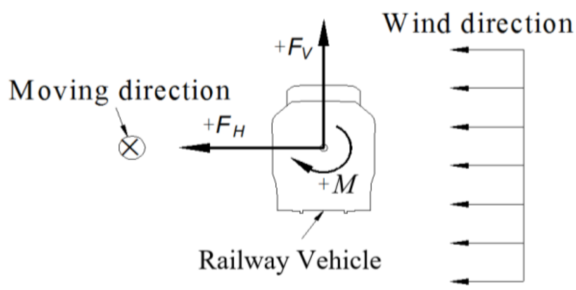
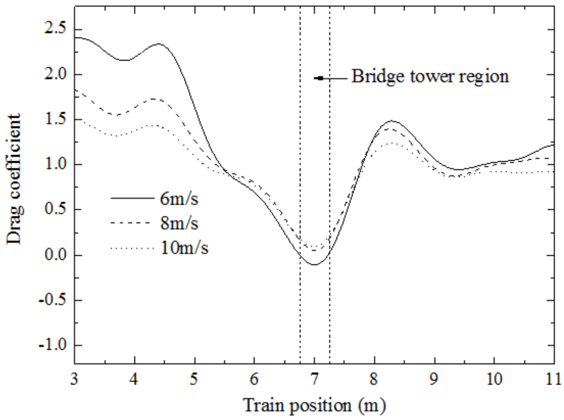
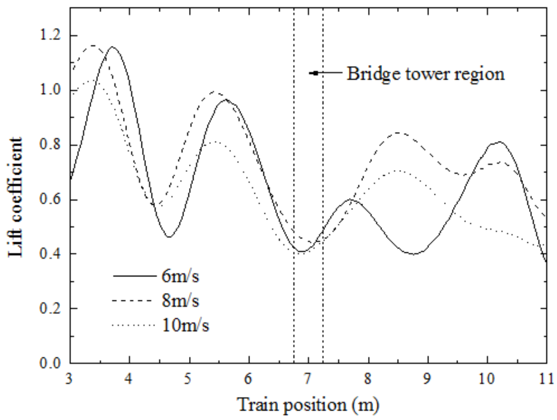


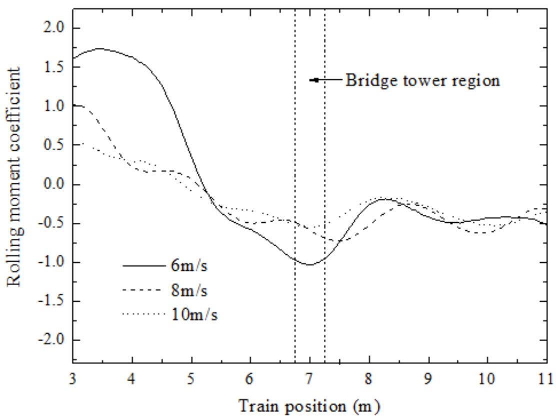
Fig. 4 Aerodynamic forces and moment acting on the railway vehicle



(a) Aerodynamic coefficient of drag force

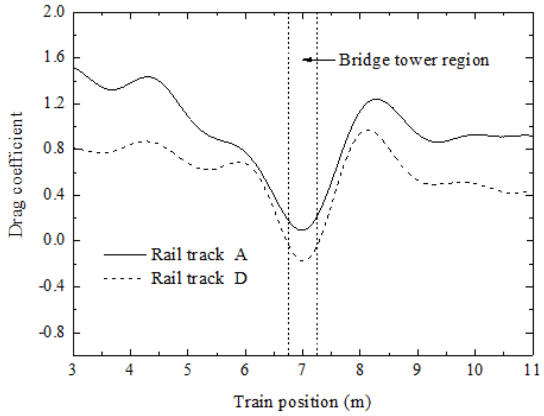


(b) Aerodynamic coefficient of lift force

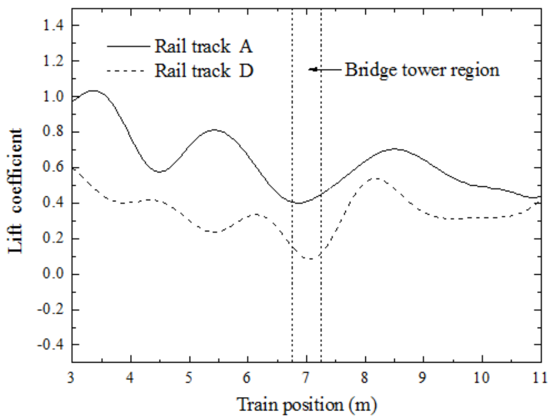


(c) Aerodynamic coefficient of rolling moment

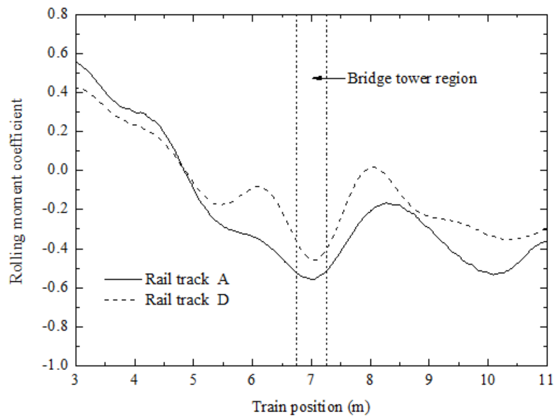
Fig. 5 Effects of different mean wind speeds on the aerodynamic coefficients



(a) Aerodynamic coefficient of drag force



(b) Aerodynamic coefficient of lift force



(c) Aerodynamic coefficient of rolling moment

Fig. 6 Effects of different rail tracks on the aerodynamic coefficients

3. Aerodynamic coefficients in the actual scale

Figs. 5 and 6 show the aerodynamic coefficients in the wind tunnel experiments. In order to consider the impacts of the wind shielding effects of bridge tower on the running railway vehicles in the actual scale, the aerodynamic coefficients that measured in the wind tunnel tests should be converted into the aerodynamic coefficients in the actual scale.

In the present moving model experiments, the angle between the mean wind direction and the vehicle moving direction is always kept constant at 90°. The yaw angle is defined as the angle between the resultant wind direction and the vehicle moving direction. Thus the aerodynamic force and moment coefficients can be taken as a function of yaw angle only (Baker 1986). The yaw angle in the wind tunnel test is identical with that in the full scale, which could be expressed as Eq. (4)

$$\frac{\overline{U}_m}{V_m} = \frac{\overline{U}_p}{V_p} \tag{4}$$

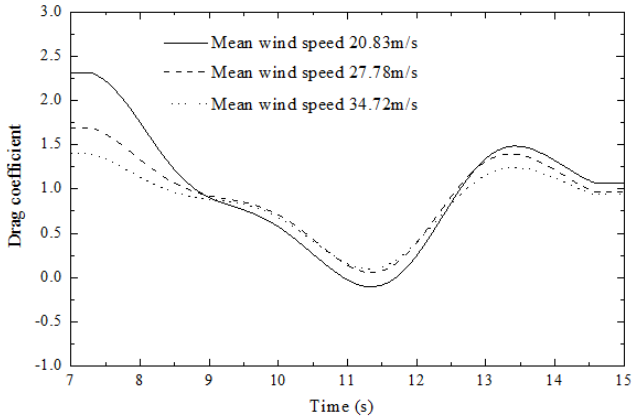
where $\overline{U}$ is the mean wind speed; V is the vehicle speed; the subscript m represents the model experiment; the subscript p represents the full scale. In the wind tunnel test, the mean wind speed is set as 6 m/s, 8 m/s and 10 m/s, respectively, and the moving speed of the vehicle model is set as 8m/s. In the present study, it is assumed that the speed of the prototype railway vehicle is 100 km/h. Therefore, the full scale mean wind speed which corresponds to the mean wind speed in the wind tunnel can be calculated from Eq. (4) as 20.83 m/s, 27.78 m/s and 34.72 m/s, respectively.

The experimental time scale needs to be considered in the moving model experiments, so that the measurement period in the experiments can be related to the equivalent full scale period (Baker 1986). Assuming that the time for the vehicle model to move a distance of s is t_m, t_p is the corresponding full scale time, V_m is the speed of vehicle model, V_p is the full scale vehicle speed and r is the geometric scale ratio (full scale to model scale, r = 45). Thus the conversion formula can be expressed as Eq. (5)

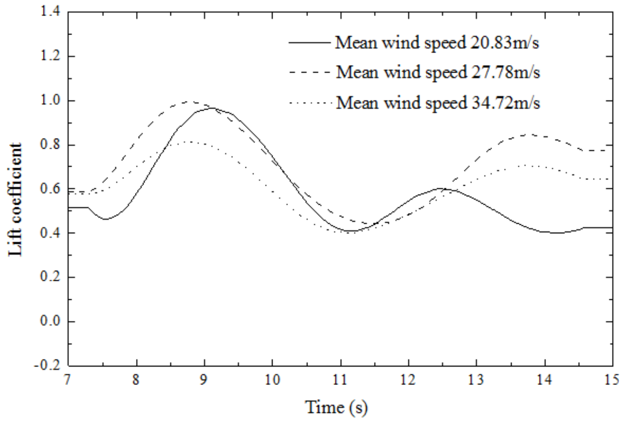
$$t_p = rs/V_p \tag{5}$$

Substituting the vehicle model running distance s into Eq. (5), the equivalent full scale time t_p corresponding to the prototype vehicle speed V_p can be calculated.

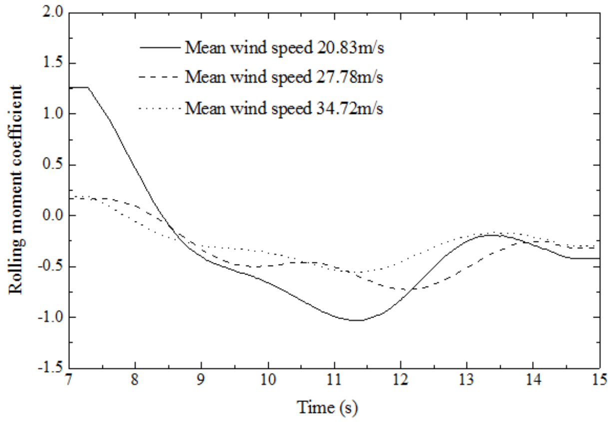
Figs.7 and 8 show the converted time histories of the aerodynamic coefficients at the full scale vehicle speed V_p of 100 km/h. When the railway vehicle moves along the rail track A, the effects of different full scale mean wind speeds on aerodynamic coefficients are shown in Fig. 7. When the railway vehicle moves along the rail track A and the rail track D, the aerodynamic coefficients are shown in Fig. 8, where the full scale mean wind speed is 34.72 m/s. As shown in the figure, the railway vehicle moves into the aerodynamic sudden-change region at $t_p = 7.29s$ and departs from the region at $t_p = 14.58s$. In the subsequent analysis, it is assumed that the aerodynamic coefficients are kept constant when the railway vehicle is out of the aerodynamic sudden-change region.



(a) Aerodynamic coefficient of drag force

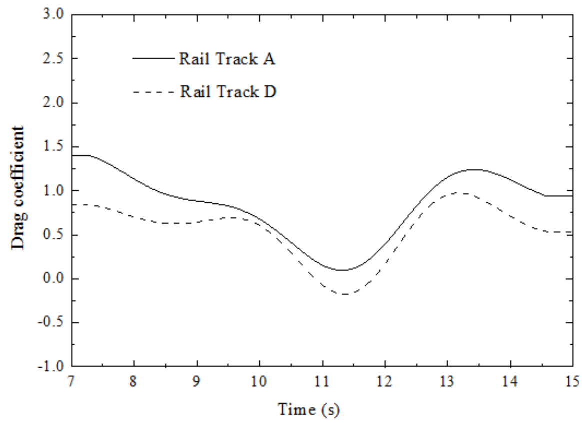


(b) Aerodynamic coefficient of lift force

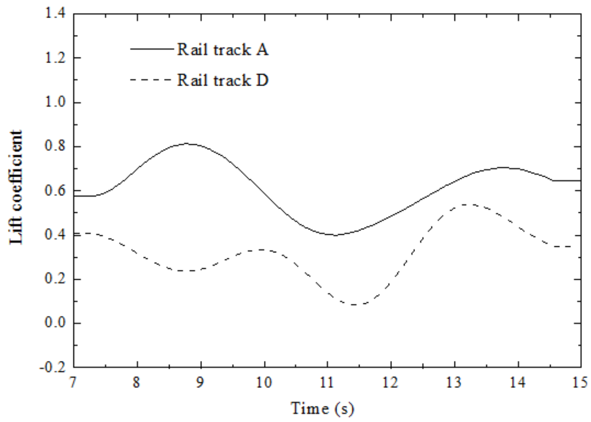


(c) Aerodynamic coefficient of rolling moment

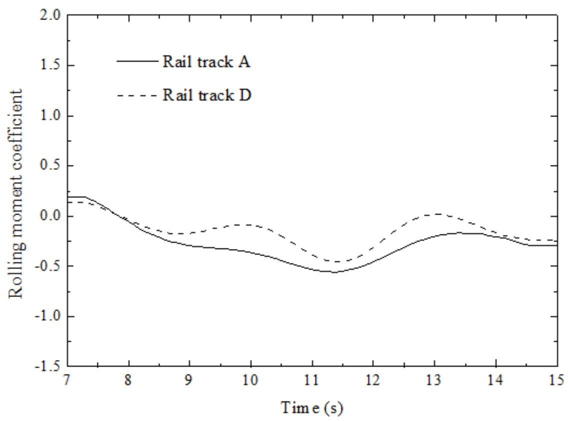
Fig. 7 Aerodynamic coefficients at different full scale mean wind speeds



(a) Aerodynamic coefficient of drag force



(b) Aerodynamic coefficient of lift force



(c) Aerodynamic coefficient of rolling moment

Fig. 8 Aerodynamic coefficients of the railway vehicle moving on different rail tracks in the actual scale

4. Multibody dynamics model

Referring to one kind of passenger railway vehicle, a corresponding 3D multibody dynamics model has been set up in the Simpack Rail Environment, which is a multibody analysis software widely used in the railway industry (Ignesti *et al*. 2012, Ignesti *et al*. 2013, Allotta *et al*. 2014, Innocenti *et al*. 2014, Zhang *et al*. 2014). In the present study, the following assumptions are made for the simulation of multibody dynamics:

1) The stiffness of the coach, bogie and wheelset is much larger than the stiffness of the suspension system. The elastic deformation of the coach, bogie and wheelset is not considered so that they are assumed as rigid bodies.

2) The engine and transmission system are not considered, but their masses and inertia moments will be incorporated into those of the wheelsets and bogies.

3) The elastic deformation of the rail track is not considered and only the track irregularities are taken into account in the present study.

The multibody dynamics model of the railway vehicle consists of one coach, two bogie frames and four wheelsets (two for each bogie). The railway vehicle is equipped with two suspension systems: the primary suspension system and the secondary suspension system. The primary suspension system includes springs and dampers, which connects the wheelsets to the bogies. The secondary suspension system connects the coach to the bogies, comprising the following elements: air springs, dampers, traction rod, anti-roll bar and lateral bump-stops. Both the primary suspension and the secondary suspension are modeled by linear or nonlinear force elements to connect the rigid bodies. The multibody railway-vehicle model is shown in Fig. 9, which includes all the significant degrees of freedom (DOF). The wheel-rail contact model is very important in the simulation of the railway-vehicle dynamics since the evolution of rail and wheel profiles has serious effects on both dynamical and stability characteristics of railway-vehicles (Ignesti *et al*. 2013, Innocenti *et al*. 2014, Meli *et al*. 2014). In this study, the contact model based on the global Hertz's theory and simplified Kalker's algorithm FASTSIM is used into the multibody railway-vehicle model to reduce the computational load. For each wheel, one contact point on the wheel tread is considered for the calculation. In addition, the aerodynamic forces and moments have great effects on the running performance of railway vehicles in crosswind conditions. In the present study, the aerodynamic forces and moment are treated as the inputs of excitation varied with time for kinetic simulation of the railway vehicle in the Simpack Rail environment.

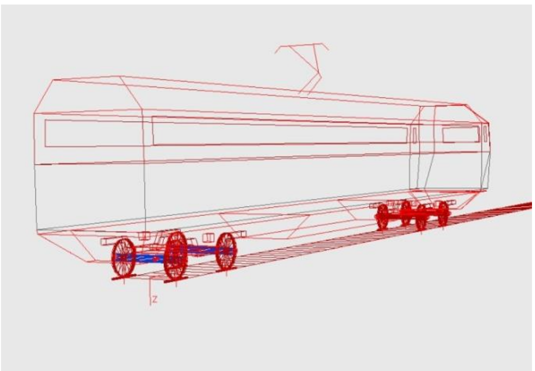
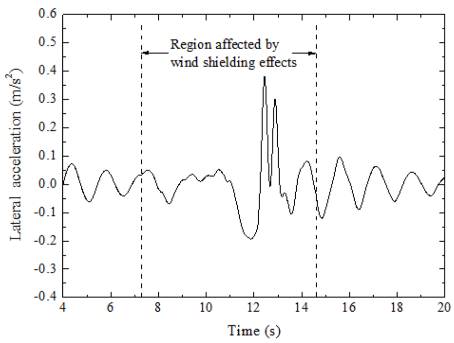


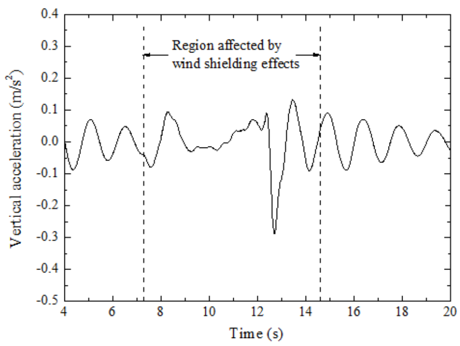
Fig. 9 Global view of the multibody model

5. Effects of sudden changes of wind loads on dynamic responses of railway vehicle

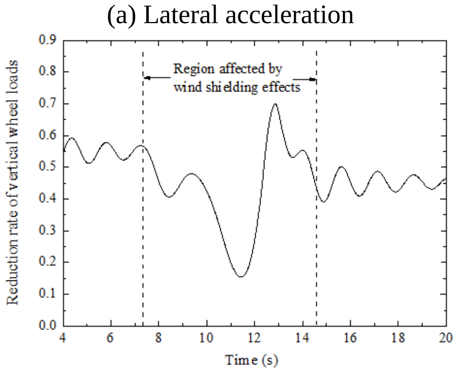
Based on the aerodynamic coefficients in the actual scale shown in Figs. 7 and 8, the aerodynamic drag force, lift force and rolling moment acting on the railway vehicle can be calculated by using Eqs. (1)-(3). The present study focuses on the sudden changes of aerodynamic loads caused by the wind shielding effects of bridge tower and the impacts of the sudden changes of aerodynamic loads on the running performance of railway vehicle, so that only the static aerodynamic loads are applied on the railway vehicle as external excitations for kinetic simulation, neglecting the effects of track irregularities and wind fluctuations. The dynamic responses of the railway vehicle passing by the bridge tower can be obtained from the kinetic simulations in the time domain. When the railway vehicle moves along the track A at the speed of 100 km/h to pass by the bridge tower under the mean wind speed of 27.78 m/s, the lateral and vertical accelerations of the vehicle body, the reduction rate of vertical wheel loads on right wheel and the derailment coefficient are shown in Fig. 10. As shown in the figure, the dynamic responses of the railway vehicle have great fluctuations and significant sudden changes in the affected region due to the wind shielding effects of the bridge tower. The sudden-change values of lateral acceleration, vertical acceleration, reduction rate of vertical wheel loads and derailment coefficient are 0.6 m/s^2, 0.43 m/s^2, 0.55 and 0.15, respectively. This indicates that the sudden changes of aerodynamic loads induced by the wind shielding effects of the bridge tower have obvious impacts on the running railway vehicle.



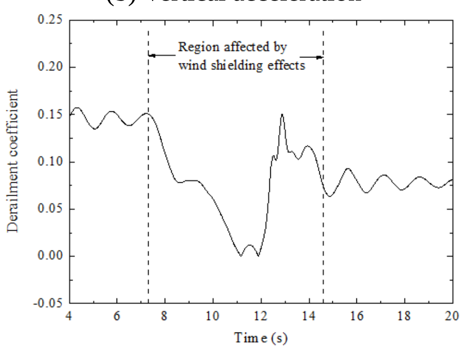
(a) Lateral acceleration



(b) Vertical acceleration



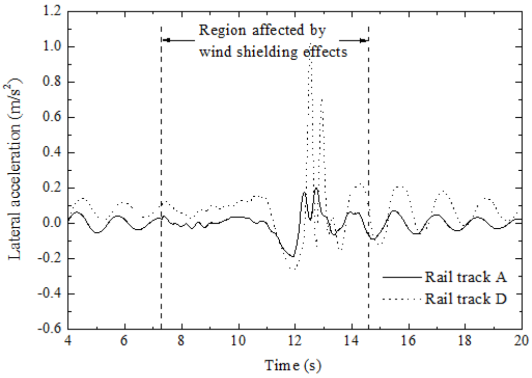
(c) Reduction rate of vertical wheel loads



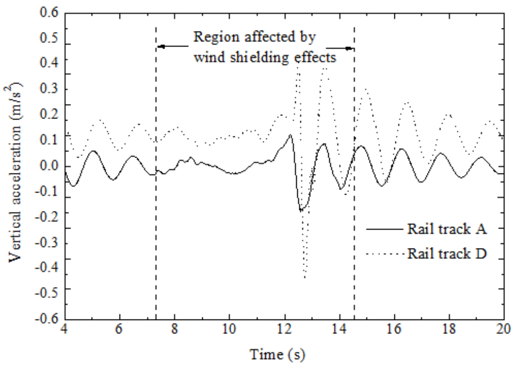
(d) Derailment coefficient

Fig. 10 Time histories of dynamic responses of railway vehicle

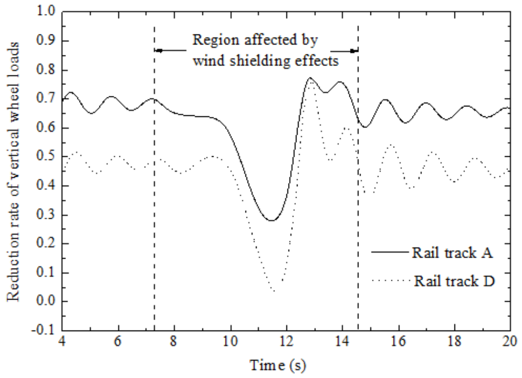
The railway vehicle is assumed to move along the rail track A at the speed of 100 km/h to pass by the bridge tower under the mean wind speed of 20.83 m/s, 27.78 m/s and 34.72 m/s. The peak values of the lateral and vertical accelerations of the vehicle body, the reduction rate of vertical wheel loads on right wheel, and the derailment coefficient are shown in Table 1. As shown in the table, the dynamic responses of the railway vehicle increase with the mean wind speed in general. When the railway vehicle moves along the rail track A and the rail track D, the kinetic simulations are conducted to investigate the wind shielding effects on the dynamic responses. The vehicle speed is 100 km/h and the mean wind speed is 34.72 m/s. Fig. 11 shows the lateral and vertical accelerations of the vehicle body, the reduction rate of vertical wheel loads on right wheel, and the derailment coefficient. The railway vehicle moving along the rail track D is found to have a more drastic sudden change in the dynamic responses, since the sudden changes of the aerodynamic loads are more dramatic when the vehicle moves along this rail track. It suggests that the wind shielding effects of the bridge tower are more adverse to the running safety and comfort of the railway vehicle which moves along in the farther track from the bridge tower in crosswind conditions.



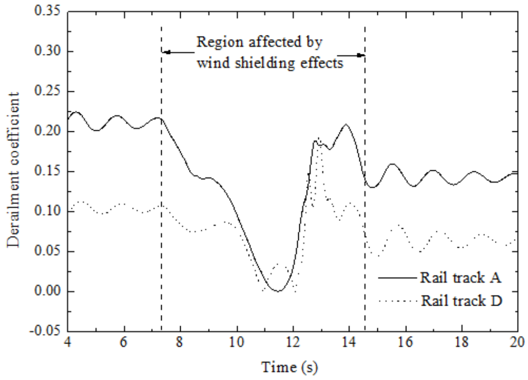
(a) Lateral acceleration



(b) Vertical acceleration



(c) Reduction rate of vertical wheel loads



(d) Derailment coefficient

Fig. 11 Time histories of dynamic responses of railway vehicle moving along different rail tracks

Table 1 Peak values of dynamic responses of railway vehicle at different mean wind speeds

Mean wind speed (m/s)	Lateral acceleration (m/s^2)	Vertical acceleration (m/s^2)	Reduction rate of vertical wheel loads	Derailment coefficient
20.83	0.172	0.118	0.374	0.098
27.78	0.381	0.288	0.700	0.157
34.72	0.204	0.176	0.772	0.225

6. Conclusions

The present study focuses on investigating the dynamic impacts of the sudden changes of aerodynamic loads on the running safety and comfort of the railway vehicle passing by the bridge tower.

- The aerodynamic coefficients of the railway vehicle have significant sudden changes due to the wind shielding effects of the bridge tower.
- The average sudden-change region of the aerodynamic coefficients is larger than the width of the bridge tower, since the vehicle-induced wind and the complex wind-structure interaction near the bridge tower can lengthen the sudden-change region.
- The sudden changes of the aerodynamic loads have obvious impacts on the running railway vehicle. The dynamic responses of the railway vehicle have great fluctuations and significant sudden changes in the affected region due to the wind shielding effects of the bridge tower.
- When the railway vehicle moves along the rail track that is father away from the bridge tower, the sudden changes of the aerodynamic loads and the corresponding dynamic responses are more dramatic, which is more adverse to the running safety and comfort of the railway vehicle passing by the bridge tower in crosswind conditions.

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