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Dynamic analysis of wind-vehicle-bridge system based on rigid-flexible coupling method

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ABSTRACT

In order to efficiently conduct the wind-vehicle-bridge (WVB) coupling analysis, an interactive method integrating finite element (FE) software ANSYS and Multibody System (MBS) software SIMPACK was presented. Two rigid-flexible methods, the Dummy Body Coupling (DBC) method and the Equivalent Flexible Track (EFT) method, were presented, and the merits and demerits were discussed. Finally, the DBC method was adopted for the analysis of the WVB system. The simulation of the WVB system based on the DBC method was verified by wind-vehicle system, wind-bridge system and vehicle-bridge system, respectively. The dynamic WVB coupling analysis of a continuous railway bridge was carried out, in which effects of different vehicle speeds and incoming wind directions were studied. Results show that the presented DBC method for the simulation of the WVB system has high computational efficiency and wide applicability, and can be repeated conveniently by other researchers.

1. Introduction

Strong crosswind is a vital problem for securing the safety of vehicles, and accidents posed by wind gusts on vehicles passing through the bridges have been reported around the world, which attracts increasing attention (Gawthorpe 1994; Johnson 1996; Baker et al. 2009). As the operating speed of train increases rapidly and the span of bridge expands progressively, the interactions among wind, vehicle and bridge become significant in the running performance, including not only the safety and comfort of the vehicles on the bridges, but also dynamic responses of the bridges (Li et al. 2013; Arvidsson and Karoumi 2014; Cai et al. 2015). Studies on the vehicles under crosswind have been carried out on the basis of two ways: static analysis on vehicle overturning and dynamic analysis of WVB system. Static analysis on vehicle overturning utilizes the equilibrium equation of wind forces on a vehicle to evaluate the critical wind speed of overturning (Hibino et al. 2009). This method does not take the interactions of vehicle and bridge into account, and cannot obtain the responses of the vehicle as well. The

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WVB system analysis is a complicated interaction process for determining the critical wind speed, based on the dynamic responses of vehicle and bridge and corresponding limited values (Cai and Chen 2004; Li et al. 2005). Traditional WVB system analyses were mostly conducted by deriving and programming the equations of motion of the system. However, the models were normally simplified by researchers based on their foci, which made it difficult for other researchers to review.

It is generally accepted that the interactions of vehicle and bridge are a coupling dynamics process consisting of the flexible bridge system and the multibody vehicle system. Owing to the fast development of commercial software and improvement of computer performance, it is more likely to carry out the WVB system analysis by making a combination of the MBS software and FE software.

The study aims at the dynamic analysis of the WVB system based on rigid-flexible coupling method, which takes advantage of the high modeling efficiency for structures of FE software and the powerful wheel-rail analysis function of MBS software. Based on commercial FE software ANSYS and MBS software SIMPACK, the rigid-flexible coupling method was studied in this paper. In Section 2, the modeling of WVB system is introduced. Two interactive methods, the DBC method and the EFT method, are illustrated in Section 3 in detail, and merits and demerits of these two methods are introduced as well. In Section 4, the presented DBC method for the WVB system is verified by the interactions of wind and vehicle, the interactions of wind and bridge, and the interactions of vehicle and bridge, respectively. Furthermore, the analysis of the WVB system for a continuous bridge based on the DBC method is carried out in Section 5.

2. Modeling of wind-vehicle-bridge system

2.1 Wind velocity fields

Wind velocity fluctuation is one of excitations for the WVB system, and the velocity fields are simulated as stationary Gaussian stochastic processes using spectral representation method (Li et al. 2004). Wind loads on a structure can be classified into three parts: static wind loads, buffeting loads and self-excited loads.

Static wind loads on vehicle and bridge deck in unit length can be expressed as follows:

$$F_{\mathrm{st}}^{\mathrm{D}} = \frac{1}{2}\rho U^2 H C_{\mathrm{D}} \tag{1}$$

$$F_{\mathrm{st}}^{\mathrm{L}} = \frac{1}{2}\rho U^2 B C_{\mathrm{L}} \tag{2}$$

$$F_{\mathrm{st}}^{\mathrm{M}} = \frac{1}{2}\rho U^2 B^2 C_{\mathrm{M}} \tag{3}$$

where F_{D}, F_{L} and F_{M} are the drag force, the lift force and the moment, respectively; ρ is the air density; U is the upstream wind velocity; C_{D}, C_{L} and C_{M} are the drag coefficient, the lift coefficient and the moment coefficient, respectively; H and B are the height and the width of the vehicle or the bridge deck.

Buffeting loads are induced by stochastic wind fluctuations. According to the quasi-steady theory, buffeting loads on the deck or the vehicle in unit length can be expressed as follows:

$$F_{\mathrm{bu}}^{\mathrm{D}} = \frac{1}{2}\rho U^2 B\left[2\frac{H}{B}C_{\mathrm{D}}\frac{u(t)}{U}\gamma_1\right] \tag{4}$$

$$F_{\mathrm{bu}}^{\mathrm{L}} = \frac{1}{2}\rho U^2 B\left\{2C_{\mathrm{L}}\frac{u(t)}{U}\gamma_2 + \left[C_{\mathrm{L}}^{'} + \frac{H}{B}C_{\mathrm{D}}\right]\frac{w(t)}{U}\gamma_3\right\} \tag{5}$$

$$F_{\mathrm{bu}}^{\mathrm{M}} = \frac{1}{2}\rho U^2 B^2\left\{2C_{\mathrm{M}}\frac{u(t)}{U}\gamma_4 + C_{\mathrm{M}}^{'}\frac{w(t)}{U}\gamma_5\right\} \tag{6}$$

where $C_{\mathrm{L}}^{'}$ and $C_{\mathrm{M}}^{'}$ are the slopes of C_{L} and C_{M}, respectively; γ_{i} (i = 1, 2, ... , 5) are the aerodynamic admittance functions, and the values of admittance function are approximated as 1.0 in this study; $u(t)$ and $w(t)$ are the wind velocity fluctuation in the wind flow direction and the vertical direction, respectively.

Since the width of the vehicle is relative small and the section is bluff, the self-excited forces on the vehicle are ignored. And the self-excited forces on the bridge deck are neglected as well.

2.2 Modeling of vehicle MBS model

A typical MBS model in SIMPACK comprises four system-defined components (body, joint, force element and external force) and other basic components. In the MBS dynamics, a body can be categorized as a rigid body or an elastic body. In SIMPACK, the joint, known as kinematic pair, is a kind of kinematic constraints. Each body has a corresponding joint to define the kinematic relationship between the bodies or body and reference coordinate system. Force element is utilized to define the interaction between the bodies in the system. External force is an action on the marker point of body in the MBS from the external system.

The train is a complicated multi-DOF spatial vibration system, of which the vibration is categorized into the lateral, longitudinal, vertical, yaw, pitch and roll motions. A high-speed train fundamentally consists of car bodies, bogies and wheelsets, which are defined by body. Wheelsets are connected with the bogie by the primary suspension system, and the bogie is jointed to car body through the secondary suspension system including air springs, lateral and vertical dampers, antiroll torsion bars, anti-hunting dampers and lateral stop using force elements. The springs and dampers, providing stiffness and damping, are defined as the spring-damping system. In addition, car body, bogies and wheelsets are considered as rigid bodies in the paper, for their stiffnesses are much larger than those of the components of the suspension system. Centroid of each body is bilaterally symmetric. A schematic model of a train is shown in Fig. 1.

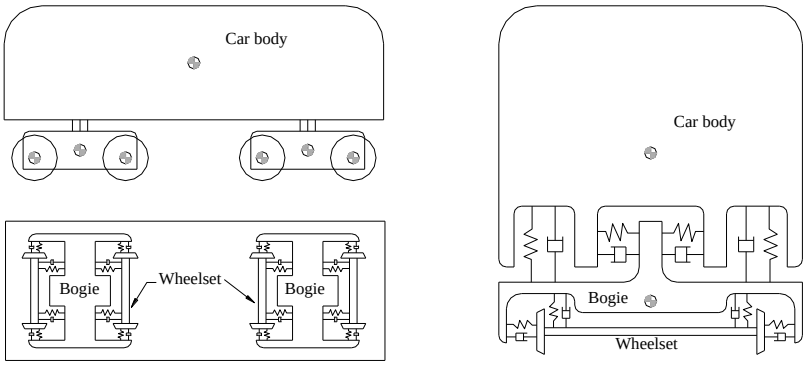


Fig. 1 Schematic model of a train

In this paper, the CRH (China Railways High-speed) train model was established in commercial software SIMPACK. The train is divided into three parts: a car body, two bogies and four wheelsets, totally seven rigid bodies. Force elements are employed to simulate the primary and secondary suspension systems. The whole vehicle is regarded as the rigid body-spring-damping system. The car body and each bogie have 6 DOFs, and each wheelset has 4 DOFs. As a result, a single train model has 34 DOFs in total. The links take into account the primary and secondary suspension system, which are simulated by force element. The stiffness and damping are defined linear or non-linear according to practical situations. One-point contact model is utilized, and the simplified theory of rolling contact (FASTSIM) (Kalker 1982) is used to obtain the creep forces.

2.3 Bridge model

The bridge models are established using the FE method. On the basis of the simplification of modeling, the FE model of bridges consists of beam element, truss element, shell element, etc. The whole modeling progress utilized the commercial software ANSYS.

3. Rigid-flexible coupling method for the simulation of the WVB system

3.1 Substructure analysis of bridge FE model

To co-simulate SIMPACK with FE software, the mass, stiffness, damping and modal matrices ought to be obtained from the FE software first. Therefore, substructure analysis should be carried out and the structure model needs to be developed as a superelement in the bridge modeling progress. Substructuring technique could condense a certain portion of elements into one unit represented as a matrix, which is referred to be the superelement. In the process of substructure analysis, DOFs of the model need to be reduced, where the Guyan condensation method (Guyan 1965) is used by identifying a set of master degrees of freedom in the present study. After substructure analysis and modal analysis, the information about mass matrix, stiffness matrix, geometry and modes are written in the files respectively and prepared to be inputted into the SIMPACK.

3.2 Inputting process from ANSYS to SIMPACK

The bridge model should be imported into the SIMPACK via the interface program FEMBS. Generated files in the substructure analysis in the FE software can be read, and the file of *.fbi (flexible body input file) and *.SID_FEM (Standard Input Data file) will be generated via the interface program FEMBS in SIMPACK.

3.3 Rigid-flexible coupling methods

One of the key issues to the WVB coupling vibration analysis is the wheel-rail contact between the vehicle and bridge in the framework of the MBS. Two rigid-flexible coupling methods are presented in the paper.

The first method is the Dummy Body Coupling (DBC) method, where the whole rigid-flexible coupling system is composed of a flexible body system (bridge structure) and a rigid body system (vehicle), and the two systems are connected by the dummy body. Here the dummy body, used as the link of the rigid and flexible bodies, has negligible mass and should make few effects on the whole coupling system. The bridge model should be inputted into the preprocessor of SIMPACK to generate the flexible body using *.SID_FEM file. The dummy body is defined to match each wheelset, as well as the moved marker on the bridge. The dummy body moves with the corresponding wheelset, and needs linking to the corresponding the moved marker on the bridge for the real-time analysis. This method provides the benefit that the preprocessor of SIMPACK defines the bridge structures and the exported points directly. In addition, any load which the analysis need take into consideration can be imposed on any position of the system as long as the corresponding wind marker of the body is defined. The WVB system based on the DBC model (Fig. 2) is regarded as a united and coupled system, and the equations of motion are solved directly.

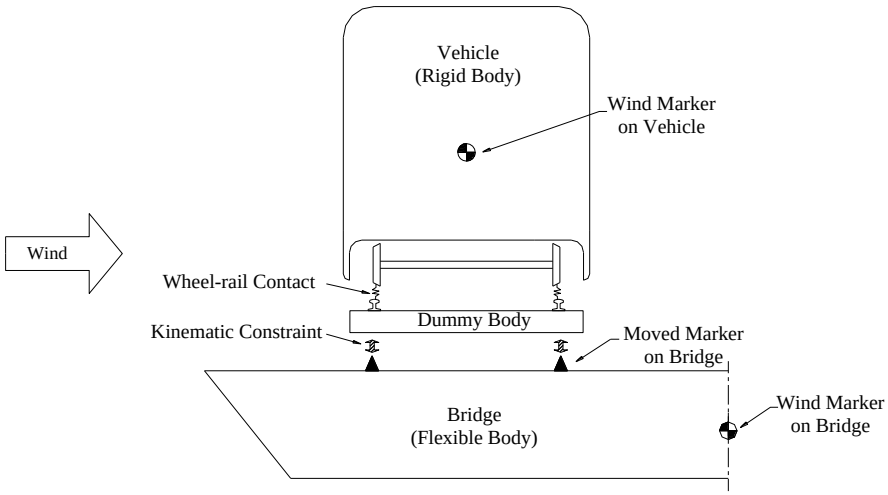


Fig. 2 WVB model based on the DBC method

The second method is the Equivalent Flexible (EFT) Track method, which makes full use of the flexible track module in the SIMPACK. The EFT method decouples the vehicle-bridge (VB) system, and the equations of motion are derived further according to the characteristics of the bridge structure. The information of the bridge is read into the SIMPACK via the flexible track module using *.fbi file. It is noted that the bridge does not exist as a flexible body by the EFT method in SIMPACK. Since the EFT

method is the derived solution of decoupled equations, the solving efficiency of the VB solution will be increased. It is noted that for the recognition of communication points, the finite model grid is demanded to be set with equal spacing, which may bring some difficulties in the bridge modeling process. In addition, since the bridge does not exist as a flexible body, the load cannot be imposed on the bridge structures, which does not fulfill the demand of the analysis of the WVB system.

Based on the introductions above, the DBC method is finally adopted in the dynamic analysis of the WVB system in this study.

3.4 Equations of motion of the bridge (flexible body) in the MBS

The bridge structure exists as a flexible body in the whole system for the DBC method. The equations of motion of a flexible body were presented in detail in the past research (Dietz et al. 2002; Rose et al. 2004). The position of an arbitrary point *P* on the flexible body can be formulated as

$$\mathbf{r}^P(\mathbf{c},t) = \mathbf{A}(t)(\mathbf{r} + \mathbf{c} + \mathbf{u}(\mathbf{c},t)) \tag{7}$$

where $\mathbf{A}$ is a rotation matrix used for the coordinate transformation from body reference system *e* to the inertial system e^I; $\mathbf{r}$ is the position of the body reference system *e* and $\mathbf{c}$ is the position of point *P* in the undeformed state in the body reference system *e*; $\mathbf{u}(\mathbf{c},t)$ is the flexible body deformation vector.

The Ritz approximation of the deformations $\mathbf{u}(\mathbf{c},t)$ of the flexible body is used with a linear combination of shape function $\boldsymbol{\varphi}_j(\mathbf{c})$ with the modal coordinate $q_j(t)$:

$$\mathbf{u}(\mathbf{c},t) = \sum_{j=1}^{n_q} \boldsymbol{\varphi}_j(\mathbf{c}) q_j(t) \tag{8}$$

Combining the Ritz-approximation with Hamilton's principle and using the variational calculus, the equations of motion are formulated (Wallrapp 1994)

$$\mathbf{M}(\mathbf{q}) \begin{Bmatrix} \mathbf{a} \\ \dot{\boldsymbol{\omega}} \\ \ddot{\mathbf{q}} \end{Bmatrix} + \mathbf{k}_\omega(\boldsymbol{\omega},\mathbf{q},\dot{\mathbf{q}}) + \mathbf{k}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{h} \tag{9}$$

where $\mathbf{M}$ is the mass matrix; $\mathbf{k}_\omega$ is the matrix of generalized forces due to gyroscopic and centrifugal terms; $\mathbf{k}$ and $\mathbf{h}$ are the matrices of internal and external generalized forces, respectively; $\mathbf{a}$, $\boldsymbol{\omega}$ and $\mathbf{q}$ are time-dependent vectors, which represent absolute acceleration, angular velocity and modal coordinate, respectively.

4. Verification of the DBC method

Before conducting the dynamic analysis of the WVB system, the DBC method should be verified first. Since the WVB system is a complicated coupling system, which consists of natural wind, dynamics of vehicle and structure dynamics of bridge, the verification was carried out through three parts: the interactions between wind and vehicle, the interactions between wind and bridge, and the interactions between vehicle and bridge.

4.1 Interactions between wind and vehicle

The interactions between wind and vehicle were verified by the static wind force applied on the car body centroid of vehicle, comparing the wind-vehicle (WV) model and the wind-vehicle-dummy body model (DBC method). A 40 kN drag force was applied on the two models, respectively. In order to alleviate the sudden impacts on the vehicle, a 2 s linear increase process of the force was considered in the investigation. The lateral displacements of the car body centroid for the two models were displayed in Fig. 3. It is shown that the results obtained from the two model are close, demonstrating that the DBC method for the interactions between wind and vehicle is feasible.

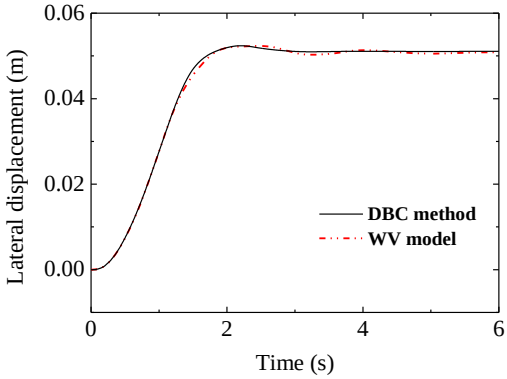


Fig. 3 Car body centroid lateral displacement under static drag force

4.2 Interactions between wind and bridge

The comparison of wind loads on the bridge was conducted, between the MBS model (DBC method) in SIMPACK and the FE model (transient analysis method) in ANSYS, by the fluctuating drag force applied on the bridge deck.

A multi-span 42 m simply-supported beam bridge was adopted. The fluctuating wind velocities were simulated using the spectral representation method. The wind velocity fields of bridge deck contained 21 wind velocity simulation points with an interval of 2 m along the deck, and the drag forces were applied on the bridge deck of one span. The lateral displacements of mid-span and quarter-span of the deck were plotted in Fig. 4, which shows that the responses of the bridge using the DBC method of MBS model quite match with those using transient analysis method of FE model.

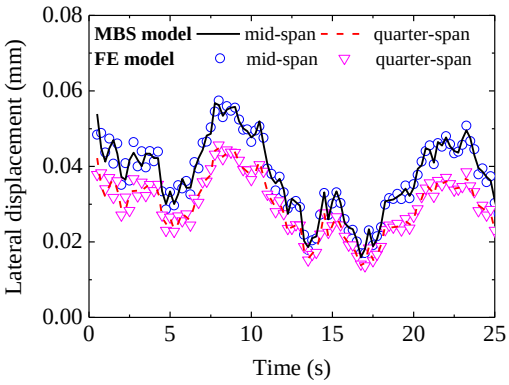


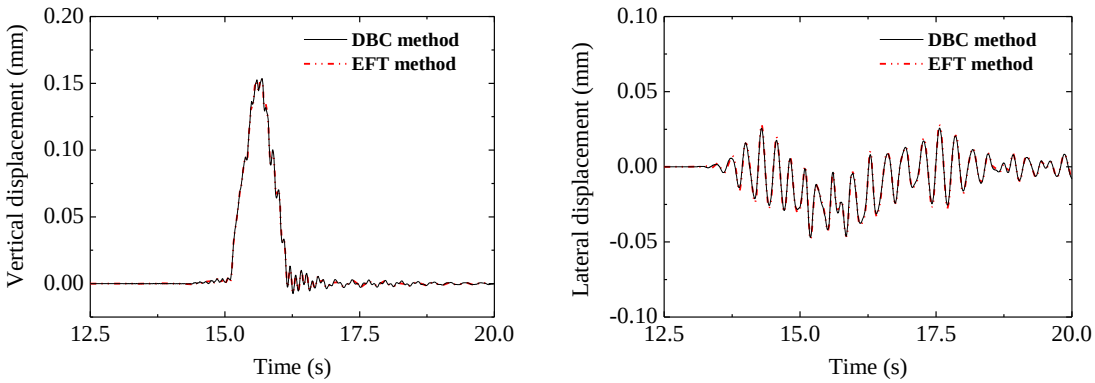
Fig. 4 Lateral displacement at the mid-span of the bridge under fluctuating drag forces

4.3 Interactions between vehicle and bridge

Interactions between vehicle and bridge include multibody dynamics of vehicle, structural dynamics of bridge and wheel-rail contact relationships. As introduced in Section 3.3, two rigid-flexible coupling methods, the EFT method and the DBC method, can realize the vehicle-bridge coupling analysis in SIMPACK. It should be noted that the EFT method is a decoupled vehicle-bridge vibration solution, which has been verified by the authors compared with the cases of vehicle passing through the bridge as static forces in ANSYS.

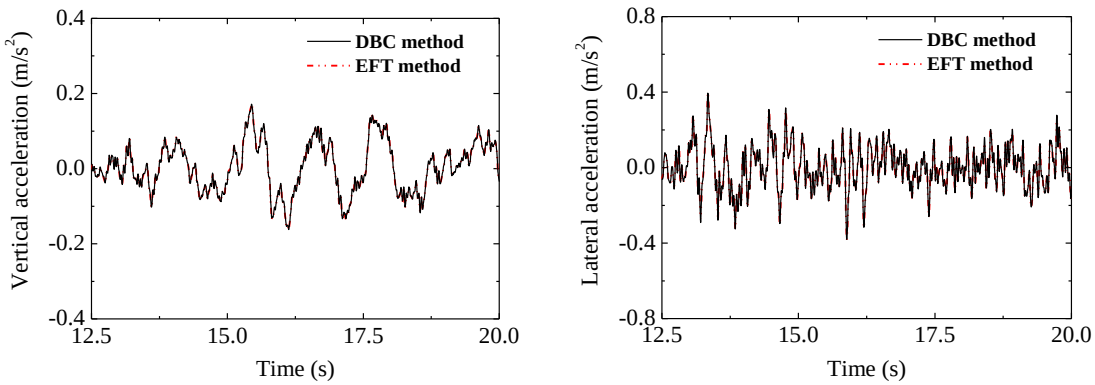
A single CRH train and a multi-span 42 m simply-supported beam bridge were adopted. The verification of interactions between vehicle and bridge was conducted by the responses of both the vehicle and the bridge. The track irregularities were generated according to the power spectrum density function of the German low-disturbance track spectrum. The vehicle speed was taken as 200 km/h. Fig. 5 displays the vertical and lateral displacements of the bridge at the mid-span. The car body centroid vertical and lateral accelerations are displayed in Fig. 6.

The results demonstrate that the dynamic responses of both the vehicle and the bridge by the two rigid-flexible coupling methods are highly close, revealing that the dummy body in the DBC method has few efforts on the whole vehicle-bridge system.



(a) Vertical (b) Lateral

Fig. 5 Displacements at the mid-span of the bridge in the vehicle-bridge system



(a) Vertical (b) Lateral

Fig. 6 Car body centroid accelerations in the vehicle-bridge system

To sum up, the DBC method for the dynamic analysis of the WVB system is verified by the interactions of interactions between wind and vehicle, the interactions between

wind and bridge, and the interactions between vehicle and bridge, respectively. The dummy body has negligible influences on the whole WVB coupling system.

5. Simulation of the WVB system

To conduct the simulation of the WVB system, a double-track railway continuous bridge and a CRH train with 8 cars (T+6×M+T; M: motor car, T: trailer car) were adopted.

The transverse distance between the track lines is 5 m, and the concrete box-girder of the bridge has a height of 3.05 m and a width of 9.06 m, and the piers are 7 m high. The FE model of the bridge was established (Fig. 7), and natural properties of main modes for the girder were listed in Table 1. Substructure analysis was carried out in ANSYS and inputted into SIMPACK as a flexible body by *.SID_FEM file.

Static wind aerodynamic coefficients of the vehicle and the bridge deck are listed in Table 2, noting that both windward and leeward vehicles are considered in the study. The track irregularities were generated according to the power spectrum density function of the German low-disturbance track spectrum. The incoming wind mean velocity was taken as U = 20 m/s, and the wind acted perpendicularly to the vehicle advancing direction. The vehicle speeds of the vehicle were set as V = 160, 200 and 250 km/h separately.

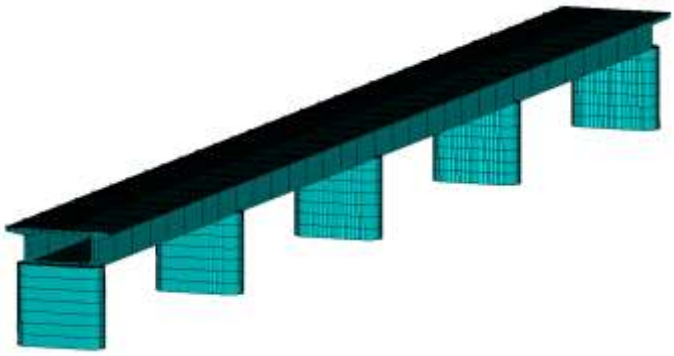


Fig. 7 FE model of the continuous bridge

Table 1 Natural properties of main modes for the girder

Mode number	Natural frequency (Hz)	Mode description
1	6.40	1st Vertical bending; asymmetric
2	7.22	1st Vertical bending; symmetric
3	12.97	1st Transverse bending; asymmetric
4	13.19	1st Transverse bending; symmetric

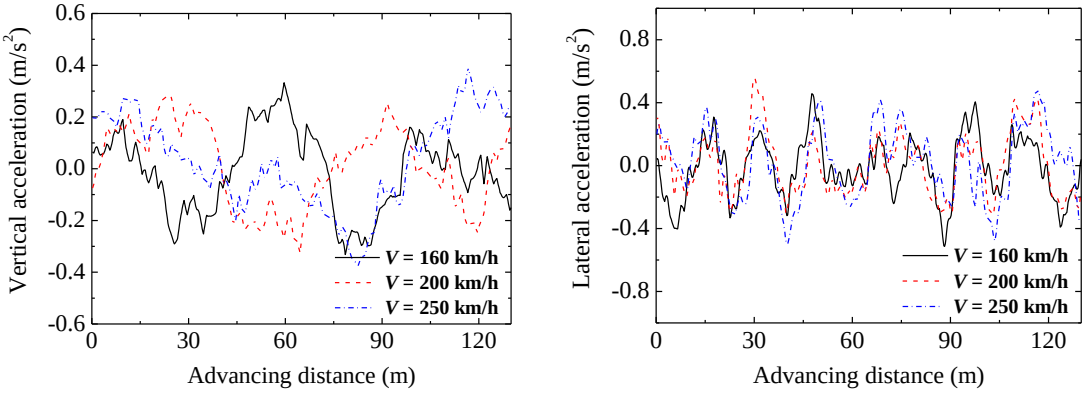
Table 2 Aerodynamic coefficients

		C_D	C_L	C_M
Vehicle	windward	1.6797	-0.0958	0.2708
(with bridge deck)	leeward	0.8574	0.5502	-0.1020
Bridge deck	windward	1.9864	-0.0115	0.0244
(with vehicle)	leeward	1.6701	-0.3023	0.0522

Bridge deck (without vehicle)	1.4229	0.4823	0.1893

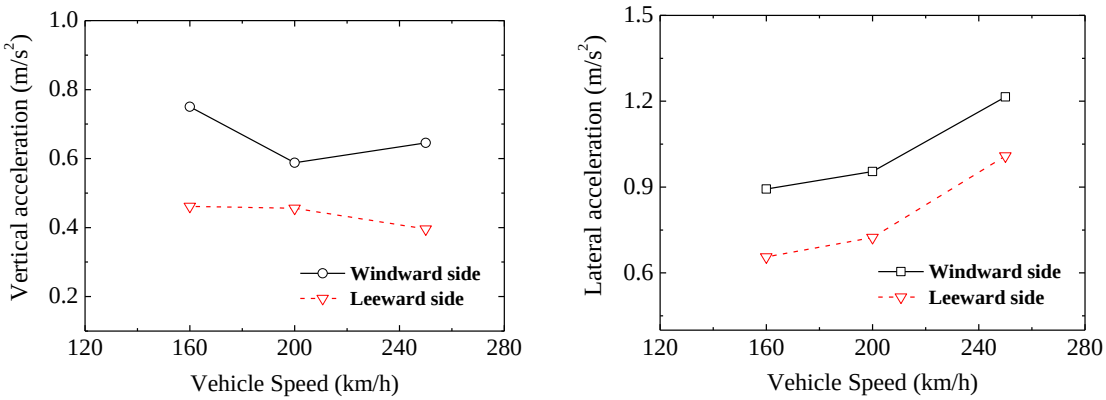
5.1 Vehicle dynamic responses

Car body centroid vertical and lateral accelerations of the first motor car at the windward side were displayed in Fig. 8. The maximum responses of the motor cars, varying with vehicle speeds and incoming wind directions, were shown in Figs. 9 to 11. It is found that lateral vibrations of the windward vehicle are stronger than those of the leeward vehicle, for the aerodynamic coefficients of the windward vehicle are much larger. With the speed of vehicle increasing, the dynamic responses generally increase.



(a) Vertical (b) Lateral

Fig. 8 Time-histories of car body centroid accelerations (Windward)



(a) Vertical (b) Lateral

Fig. 9 Maximum car body centroid accelerations

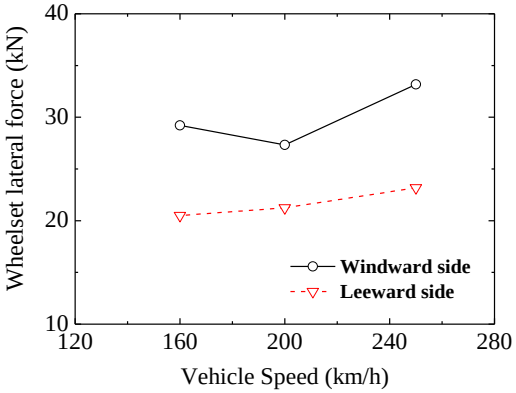


Fig. 10 Maximum wheelset lateral force

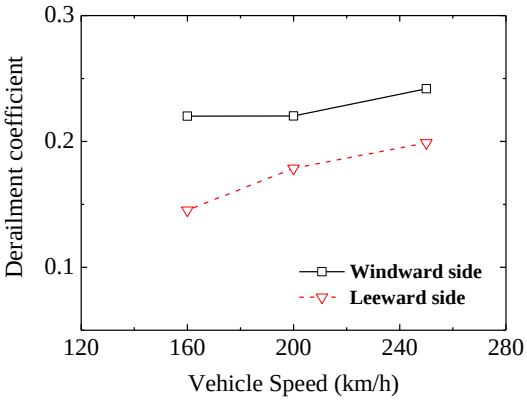
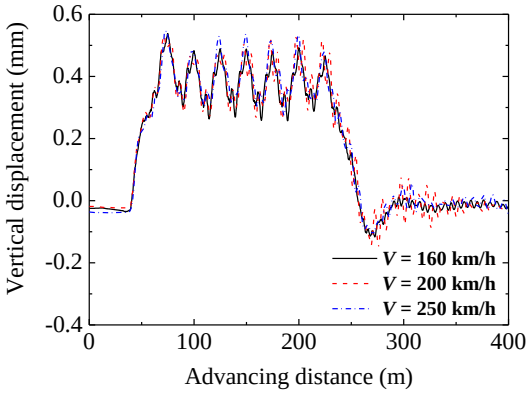


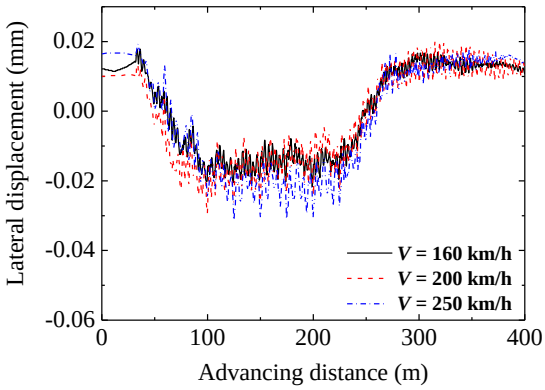
Fig. 11 Maximum derailment coefficient

5.2 Bridge dynamic responses

Figs. 12 and 13 give the time-histories of displacements and accelerations at the mid-span of 1st span (side span) in the vertical and lateral directions. It is observed that the vertical displacement of the bridge is mainly affected by the vehicle vertical loads, while the lateral displacement of the bridge is affected by both the vehicle partial loads and the wind drag loads. It is shown that the dynamic impact effects of the vehicle expand with the vehicle speed increasing.

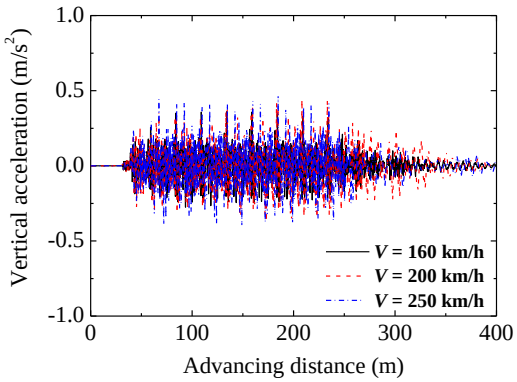


(a) Vertical

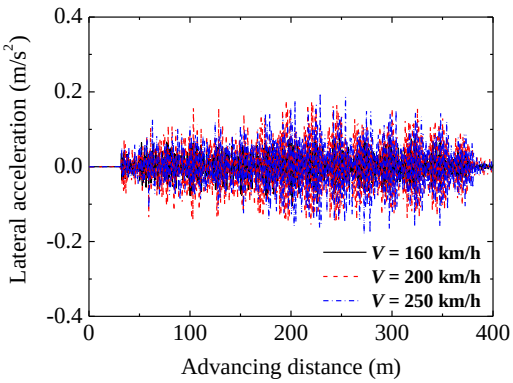


(b) Lateral

Fig. 12 Time-histories of displacements at the mid-span of 1st span (Windward)



(a) Vertical



(b) Lateral

Fig. 13 Time-histories of accelerations at the mid-span of 1st span (Windward)

6. Conclusions

In this study, the rigid-flexible coupling method, the DBC method, to conduct the simulation of the WVB system is presented. The method takes advantage of the high modeling efficiency of FE software ANSYS and the powerful wheel-rail analysis function of MBS software SIMPACK. The DBC method for the simulation of the WVB system was verified by the interactions between wind and vehicle, the interactions between wind and bridge, and the interactions between vehicle and bridge, respectively. The dummy body has negligible influences on the whole WVB coupling system.

The dynamic performances of vehicles and the double-track railway continuous bridge under strong winds were carried out, and effects of different vehicle speeds and incoming wind directions were studied. Lateral vibrations of the windward vehicle are stronger than those of the leeward vehicle, for the aerodynamic coefficients of the windward vehicle are much larger. The vertical displacement of the bridge is mainly affected by the vehicle vertical loads, while the lateral displacement of the bridge is affected by both the vehicle partial loads and the wind loads. It is shown that the dynamic impact effects of the vehicle expand with the vehicle speed increasing.

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