Vehicle-Bridge Dynamics Interaction Characteristics of High-speed Trains Passing on Bridge at the Same Speed

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ABSTRACT

Based on the theory of 3D unsteady turbulence and dynamics of rigid-flexible multi-body system, a railway train-bridge interaction model was established, the air pressure pulse was taken into account, in order to analyze the influence of wind load to the train-bridge system when two high speed trains meeting on the bridge. A 40m freely supported beam bridge model was created, which will probably be used for higher speed railway in future. Safety, ride comfort, displacements, impact coefficient, accelerations and other dynamical variables were analyzed during the numeric simulation. The results show that the dynamical responses of train and bridge increase with the speed, except that the vertical displacement of bridge, which firstly decreases and then increases as the speed increases. The pressure of wind has much more influence on the vertical responses of train than lateral responses, and little influence to the bridge. Taking lateral acceleration and Sperling index as safety criteria for train, the maximal meeting speed for high speed trains on bridge is 450km/h. Considering the high-speed trains passing on the bridge, the impact factor of the bridge will be greater than that of the existing standard.

KEYWORDS: High-Speed Railway; Bridge; Vehicle-Bridge Dynamics Interaction; Trains Passing Each Other; Air Pressure Pulse; Finite Element Method

1 INTRODUCTION

As the core equipment of high-speed railway system, the research on its dynamic performance has been an important issue in the field of high-speed train[1-2]. When the two cars rendezvous, the transient pressure impact on the car body surface has an important influence on the running stability, safety and the structural strength of the car body. As the train speed becomes higher and higher, the impact will be more and more serious[3-4]. In order to ensure the smoothness and comfort of high-speed trains and to save land resources, high-speed train lines are heavily used in the form of bridges. The dynamic interaction between high-speed train and track system and under-track bridge structure becomes a complicated random vibration problem[1-2]. After considering the transverse wind loads such as train rendezvous pressure, the dynamic interaction of randomness will be more complicated. Diana et al. [6] first studied the additional dynamic effect of a moving vehicle with a transverse mean wind pressure on the bridge structure. Xia He et al. [7] analyzed the vibration characteristics of Tsing Ma Bridge in Hong Kong under the combined effect of wind speed field and train load, and studied the effect of wind-induced vibration on the coupled vibration system of vehicle-bridge. Li Yong-le [8-9] studied the effects of different wind field models on the dynamic response of the wind-vehicle-bridge system such as wind speed, vehicle speed, track irregularity and vehicle-bridge position. Li
Xiao-zhen et al. [10-11] use Taylor's "frozen" flocculent hypothesis to study the wind speed spectrum of vehicles at different vehicle speed / wind speed ratios under horizontal crosswind. Tian Hong-qi et al.[12-16] studied the characteristics of pressure waves at the intersection of high-speed trains at different line spacing by means of actual measurement and numerical simulation. Qi Yan-hong et al. [17-18] conducted a numerical simulation study on the aerodynamic problems of open-air trains, and presented a new formula for the change of the pressure wave amplitude on the surface of the car body during constant velocity intersections. Dong Ya-nan[19] simulated the change of the body pressure wave of the CRH2 high-speed train on the bridge. He believed that the bridge structure changed the lateral moment of the car body, which made the vehicle on the bridge more dangerous.

The aerodynamic effects of train rendezvous involve multiple disciplines intersections such as aerodynamics and railway system dynamics. Accurate numerical simulations have always been the bottleneck to solving related practical engineering problems. In order to adapt to the more rapid development of the 40m simple-supported girder bridge, the three-dimensional hydrodynamic calculation method is used to accurately solve the air pressure wave acting on the train and output it to the coupled dynamic model of the vehicle-bridge system. The coupling and simulation of aerodynamics and rail system dynamics was conducted to study the dynamic characteristics of the vehicles and bridges when the electric multiple units(EMUs) meet on ultra-high speed conditions on large-span bridges, and the high-speed EMUs' ultra-high-speed intersections were proposed. The safety speed recommendation value provides theoretical support for further improving the EMUs' ultra-high speed dynamic assessment technology and the dynamic design of large-span bridge structures.

2 VEHICLE-BRIDGE COUPLED DYNAMIC INTERACTION ANALYSIS MODEL CONSIDERING VEHICLE INTERSECTION

2.1 Two-vehicle intersection system model on the bridge

Based on the dynamics theory of soft rigid body system, the vehicle subsystem and the bridge finite element subsystem are coupled together through the wheel-rail relationship, and a vehicle-bridge dynamic interaction model considering the aerodynamic wind pressure was established (Fig.1) to study the pressure of the rendezvous. The impact of waves on the vehicle-bridge system.

![Fig.1](image1.png) Fig.1 The analysis scheme of VBI considering rendezvous ; Fig.2 The scheme of the rigid body DOFs.

2.2 Vehicle subsystem model

The 3D model of the EMUs vehicle model was adopted, and the non-Hertz multi-point contact theory was adopted for the wheel-rail contact[20-21]. Each section consists of a car body, two bogies, four wheelsets, eight axleboxes, and first and second suspension systems. Consider the stiffness of one suspension and the nonlinear characteristics of the damper. Consider the body and steering. Horizontal stop between the frame, anti-rolling torsion bar and traction center. The body, bogie bogies, and wheelsets have six degrees of freedom (DOFs). The axlebox only considers the nod of the head, as shown in Fig.2, which means that there is a total of 50 DOFs per vehicle, as shown in shown in Tab.1. The equation of motion of the vehicle is:

\[
M_v \ddot{X}_v + C_v \dot{X}_v + K_v X_v = P \tag{1}
\]

where \(M_v\), \(C_v\), \(K_v\) respectively represent the mass, damping and stiffness matrix of the vehicle; \(X_v\), \(\dot{X}_v\), \(\ddot{X}_v\) respectively represents the displacement, velocity, and acceleration column vectors of
the vehicle's DOFs; \( P \) is a load vector and consists of two parts, the formula is as follows:

\[
P = F_v + P_v
\]

(2)

where \( F_v \) is the wind load vector acting on the vehicle, which is the wind pressure load of the vehicle such as the one considered in this article; \( P_v \) is the load vector that acts on the individual degrees of the vehicle during the vibration.

### Tab.1 Degrees of freedom (DOFs) of vehicle dynamic model

<table>
<thead>
<tr>
<th>Degrees of freedom</th>
<th>Roll motion</th>
<th>Pitch motion</th>
<th>Yaw motion</th>
<th>Longitudinal motion</th>
<th>Lateral motion</th>
<th>Vertical motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car body</td>
<td>( \theta_c )</td>
<td>( \phi_c )</td>
<td>( \psi_c )</td>
<td>( x_c )</td>
<td>( y_c )</td>
<td>( z_c )</td>
</tr>
<tr>
<td>Bogie frame (i=1~2)</td>
<td>( \theta_{fi} )</td>
<td>( \phi_{fi} )</td>
<td>( \psi_{fi} )</td>
<td>( x_{fi} )</td>
<td>( y_{fi} )</td>
<td>( z_{fi} )</td>
</tr>
<tr>
<td>Wheelset (i=1~4)</td>
<td>( \theta_{wi} )</td>
<td>( \phi_{wi} )</td>
<td>( \psi_{wi} )</td>
<td>( x_{wi} )</td>
<td>( y_{wi} )</td>
<td>( z_{wi} )</td>
</tr>
<tr>
<td>Axlebox (i=1~8)</td>
<td>-</td>
<td>( \phi_{ai} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2.3 **Bridge subsystem model**

In the mutual analysis of vehicle-bridge dynamics, it was generally considered that there were no mutual displacements between the bridges on the bridge, the base plate, etc., and the deformation of the rubber mats and fasteners was ignored, that was, the deformation of the bridge was consistent with the deformation of the track[22]. Therefore, the equations of motion of each node of the bridge are:

\[
M_B \ddot{x}_B + C_B \dot{x}_B + K_B x_B = P_B
\]

(3)

where \( M_B, C_B, K_B \) respectively represent the mass, damping and stiffness matrix of the bridge structure; \( x_B, \dot{x}_B, \ddot{x}_B \) represents the displacement, velocity, and acceleration column vectors of the degree of freedom of the bridge structure; \( P_B \) is that the vehicle on the bridge acts on the individual load of the bridge, which is a function of the vibration state of the vehicle on the bridge.

2.4 **Vehicle-bridge coupling system simulation**

The dynamic analysis method of the bridge system adopts the vibration mode superposition method, then the dynamic equation of the vehicle-bridge coupling system considering the wind pressure load is[22]:

\[
\begin{align*}
M_v \ddot{x}_v + C_v \dot{x}_v + K_v x_v &= F_v + P_v \\
\dot{x}_B + 2\xi \omega \dot{x}_B + \omega^2 x_B &= \phi^T P_B
\end{align*}
\]

(4)

where \( \xi, \omega \) is the vibration mode damping ratio and the circular frequency of the bridge respectively.

The system equations are solved using the time-step iterative method, and the solution that satisfies the relationship between the motion state and the force was obtained through the iteration between the subsystems in each time step.

3 **ANALYSIS OF AIR PRESSURE WAVE LOAD AT TRAIN RENDEZVOUS**

3.1 **Flow field description equation**

The flow field around the vehicle when the two vehicles meet is a compressible, viscous, unsteady turbulent flow field[17]. The control differential equations are:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}_j) = 0
\]

\[
\frac{\partial (\rho \mathbf{u}_j)}{\partial t} + \nabla \cdot (\rho \mathbf{u}_j \mathbf{u}_j) = -\nabla p + \nabla \left( \rho \mathbf{u}_j \right) \left[ \mu \left( \frac{\partial \mathbf{u}_j}{\partial x_i} + \frac{\partial \mathbf{u}_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial \mathbf{u}_k}{\partial x_k} \right) \right]
\]

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \mathbf{u}_j (\rho E + \rho \mathbf{u}_j \cdot \mathbf{u}_j)) = \frac{\partial}{\partial x_j} \left( k \frac{\partial T}{\partial x_j} + u_i T_{ij} \right)
\]

\[p = R \rho T\]

\[
\mu_t = C_u \frac{\rho k^2}{\varepsilon}
\]

where \( u_i (i = 1, 2, 3) \) or \( u_j (j = 1, 2, 3) \) is flow velocity around the train; \( \rho \) is air density; \( x_i (i = 1, 2, 3) \) or \( x_j (j = 1, 2, 3) \) is the three components of the coordinates; \( p \) is pressure; \( \delta_{ij} (i = 1, 2, 3; y = 1, 2, 3) \) is Kronecker delta; \( \mu \) is the aerodynamic viscosity; \( T \) is the absolute temperature; \( c_i \) is the specific heat; \( K \) is the heat transfer coefficient; \( R \) is a gas constant; \( \mu_t \) is the eddy viscosity coefficient; \( k \) is turbulent kinetic energy; \( \varepsilon \) is the turbulence dissipation rate; \( C_u \) is the turbulence constant, specific visible literature [17].

### 3.2 Pressure wave numerical simulation and result verification

Using FLUENT to establish a high-speed EMUs aerodynamic model, as shown in Fig.3. The outer domain is a rectangular parallelepiped with a length of 2453 m, a width of 200 m, and a height of 100 m. The distance between the longitudinal heads of the trains was 1053 m, the distance between the lines was 5.0 m, and the distance was 500 m from the rear of the calculation area. The electric multiple units were symmetrically arranged. The velocity boundary sets different velocity boundaries according to the actual simulation vehicle speed. The fixed wall boundary was non-slip, and the relative velocity near the wall surface was zero. The wall surface and the ground surface of the train were all simulated using the standard wall surface function. QUICK format was used in the simulation.

![Fig.3 The 3D model of aerodynamic force for EMUs; a) Aerodynamic calculation model for train rendezvous; b) Train aerodynamic model.](image)

In order to verify the correctness of the train aerodynamic model, simulations and test EMUs with the same model, the same grouping, the same line spacing, and the same speed were taken. The comparison results are shown in Tab.2 and Fig.4.

### Tab.2 The results comparison of simulation and test(peak to peak)

<table>
<thead>
<tr>
<th>Positions</th>
<th>Test/Pa</th>
<th>Simulation/Pa</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th train windows</td>
<td>1631</td>
<td>1496</td>
<td>8.27%</td>
</tr>
</tbody>
</table>
Fig. 4 The aerodynamic force-time curves of test and simulation for EMUs body on the same measure point; Fig. 5 The box beam cross section (units: cm)

Tab. 1 and Fig. 4 show the results of wind pressure test and simulation at the same measuring point when the open-line train meets a speed of 400 km/h. The comparison shows that the calculation results of the aerodynamic model are basically consistent with the measured results. The results of the calculation model can be used as the wind pressure load of the aforementioned intersection.

As mentioned above, the car body motion can be simplified into six directions of motion. Therefore, the wind pressure at the intersection of the train can be equivalent to the time history curve of the force at the center point of the car body, which is equivalent to the lateral body force and transverse moment. With longitudinal moments, this load is added as an external excitation load to the vehicle-bridge coupling system.

4 ANALYSIS OF VEHICLE-BRIDGE COUPLING VIBRATION ON BRIDGE CROSSING

4.1 Case background

Taking a 40m standard double-axle simply supported girder bridge with a design speed of 350km/h as an example, this paper analyzes the dynamic characteristics of the double-axle bridge meeting at higher speeds. The deck width is 12.6m, the beam length is 40.6m, the calculated span is 39.3m, the center distance of the lateral support is 4.4m, and the beam height is 3.235m. The section is shown in Fig. 5.

(1) The bridge subsystem adopts ANSYS software SOLID185 to establish a three-dimensional solid model. The second-stage bridge load was simulated by the quality unit, and was constrained by the actual simple-supported construction model.

(2) The vehicle used the aerodynamic calculation of the same model of 8 group EMUs. The grouping form was T+M+T+M+T+M+T+M+T′ (T is trailer vehicle, M is motor vehicle). The wheel tread profile was S1002G, the rail type profile was China T60, the nominal rolling circle radius was 920mm, a multi-point non-hertz contact Kik-Piotrowski model be used on wheel-rail creep force model [22].

(3) The irregularity using time-domain irregular samples transformed from ballistic track irregularity spectrum of China's high-speed railway as an irregularity stimulus. The amplitude vertical profile amplitude is from -1.97mm to 1.93mm, cross level amplitude is from -2.56mm to 2.02mm, alignment amplitude is from -2.02mm to 2.06mm and gauge amplitude is from -1.66mm to 1.83mm.

(4) Analytical conditions as shown in Tab. 3, 350 km/h as a benchmark, the train speed was increased and the impact of intersection speed was compared. Working conditions 1 and 2 compare the impact of wind load on each index, and conditions 2 to 5 compare the impact of vehicle speed on each index.

Tab. 3 The analysis conditions

<table>
<thead>
<tr>
<th>Analysis conditions</th>
<th>Speed</th>
<th>Wind pressure</th>
<th>Marked</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350 km/h</td>
<td>Not consider</td>
<td>350</td>
</tr>
<tr>
<td>2</td>
<td>350 km/h</td>
<td>Consider</td>
<td>350+W</td>
</tr>
<tr>
<td>3</td>
<td>400 km/h</td>
<td>Consider</td>
<td>400+W</td>
</tr>
<tr>
<td>4</td>
<td>450 km/h</td>
<td>Consider</td>
<td>450+W</td>
</tr>
<tr>
<td>5</td>
<td>500 km/h</td>
<td>Consider</td>
<td>500+W</td>
</tr>
</tbody>
</table>

(5) The vehicle safety index mainly analyzes the derailment quotient, rail/wheel dynamic ratio, wheel-rail lateral force, and axle lateral force. The vehicle stability index adopts vehicle body acceleration, body Sperling and vehicle body dynamic deflection, and bridge vibration characteristics select cross-section displacement, impact coefficient, acceleration.

In order to analyze the dynamic characteristics of the vehicle-bridge system, the analysis points of the vehicle body and the bridge was selected, as shown in Fig. 5a) and 5b). The bridge system was compared with the displacement, impact coefficients, and accelerations at different measuring point of
the cross-section of the bridge. The comparison results for various conditions are shown in Fig.8, Tab.4, Fig.9, and Tab.5.

Fig.5 The schematic diagram of different measure points; a) Vehicle Body Transverse Measurement Point; b) Bridge section point.

4.2 Analysis of vehicle safety indicators

(1) Comparing analysis conditions 1 to 2, we can see that considering the wind pressure at the rendezvous has little effect on the derailment coefficient and rail/wheel dynamic ratio, it has a great influence on the wheel-rail lateral force and the axle lateral force;

(2) Comparing analysis conditions 2 to 5 shows that the vehicle safety indexes increase with the increase of the intersection speed, and the influence of the intersection wind pressure load on the wheel-rail lateral force and the axle laterality is higher than that of the derailment coefficient and the wheel load reduction rate. The effect is more pronounced;

(3) From Fig.6b), it can be seen that after the intersection speed exceeds 400km/h, the wheel load reduction rate will exceed the 0.65 limits of the "Technical Regulations for Dynamic Acceptance for High-Speed Railways Construction " (TB 10761-2013), but the wheel load reduction is mainly used for judging the vertical response index of the wheel track, and is mainly affected by the geometric state of the track. Therefore, under the conditions of the existing 350km/h high-speed irregular spectrum, it is not suitable to conduct the high-speed intersection test.

Fig.6 The comparison of vehicle safety indexes in different analysis conditions; a) Derailment quotient compared; b) Dynamic factor on the rail/wheel level compared; c) Total lateral force
4.3 Analysis of vehicle stability index

(1) Comparative analysis of conditions 1 and 2 shows that it is more significant to consider the effect of rendezvous wind pressure on vehicle body lateral acceleration, lateral Sperling and vehicle body dynamic offset than vehicle body vertical acceleration and vertical Sperling.

(2) Comparing analysis conditions 2 to 5, the vehicle body acceleration, Sperling and dynamic offset increase with the increase of the intersection speed, and the impact on the trailer is more obvious than that of the moving vehicle.

(3) It can be seen from Fig.7a) and b) that when the speed of the intersection exceeds 450km/h, the lateral acceleration of the vehicle body will exceed the level II standard of "High-Speed Railway Ballastless Track Maintenance Rule (Trial)" (TG/GW115-2012). The limit value is 0.9m/s², but it does not reach the Class III standard limit of 1.5m/s², and the transverse Sperling of the car body will exceed the limit of 3.0 in the "Dynamic Acceptance for High-Speed Railways Construction" (TB 10761-2013), so the speed of the two vehicles will meet. The speed should be controlled within 450km/h more secure.

4.4 Analysis of dynamic displacement of bridges

(1) Comparative analysis of working conditions 1 and 2 shows that the wind pressure of the rendezvous basically has no effect on the vertical displacement of the bridge, and has little effect on the displacement of the transverse roof (1# to 3#), but has no effect on the floor(4# to 5#).

(2) Comparing analysis conditions 2 to 5 shows that the lateral displacement of the simple-span box girder with the intersection increases as the program increases first and then decreases, but the vertical displacement decreases first and then increases with increasing velocity;

(3) As shown in Fig.8a) and b), the lateral displacement of the bridge is generally higher than that of the bottom plate, and the maximum lateral displacement occurs at the cantilever end of the top plate(3#). The vertical displacement of the bridge is basically the same with no obvious change, the maximum vertical displacement occurs at the center of the top plate(1#);
4.5 Impact factor analysis of bridge

(1) The comparative analysis of working conditions 1 and 2 shows that after considering the wind pressure load, the impact coefficient of the bridge has a certain increase, but it is not obvious;
(2) Comparative analysis of conditions 2 to 5 shows that with the increase of the intersection speed, the impact coefficient of the bridge first decreases and then increases, and the impact of the box girder at 400 km/h (3rd condition) is the smallest;
(3) For the box girder structure, the impact coefficient of the center part (1#) of the top plate is the largest, exceeding the value of the value of the shock coefficient of the "Code for Design of High-Speed Railway" (TB 10621-2014) of 1.057.

Tab.4 The comparison of impact factor of bridge in different analysis conditions

<table>
<thead>
<tr>
<th>Points</th>
<th>Analysis conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>1.172</td>
</tr>
<tr>
<td>2#</td>
<td>1.140</td>
</tr>
<tr>
<td>3#</td>
<td>1.124</td>
</tr>
<tr>
<td>4#</td>
<td>1.127</td>
</tr>
<tr>
<td>5#</td>
<td>1.135</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.172</td>
</tr>
</tbody>
</table>

4.6 Acceleration analysis of bridge

(1) Comparative analysis of working conditions 1 and 2 shows that the cross-wind acceleration of the cross-bridge of the bridge is more obvious than the vertical acceleration;
(2) Comparative analysis of conditions 2 to 5 shows that the bridge-to-center acceleration shows an increasing trend with the increase of the intersection speed, and for the vertical acceleration, the center point (1#) and the cantilever end (3#) of the roof increase more obviously;
(3) As can be seen from Table 5, the vertical acceleration of the bridge panel at each measuring point under the action of the forced frequency of 20 Hz and below is 1.098 m/s², which is less than the 5.0 m/s² specified in the "Code for Design of High-Speed Railway" (TB 10621-2014).

Fig.9 The acceleration contrast of bridge middle cross section in different analysis conditions (peak value); a) Compared of lateral acceleration in bridge mid-section; b) Compared of vertical acceleration of cross section of bridge.

Tab.5 The vertical acceleration of 20Hz filtering for different measure points on bridge deck (units: m/s²)

<table>
<thead>
<tr>
<th>Points</th>
<th>Analysis conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>0.569</td>
</tr>
<tr>
<td>2#</td>
<td>0.445</td>
</tr>
<tr>
<td>3#</td>
<td>0.569</td>
</tr>
</tbody>
</table>
5 CONCLUSIONS

(1) The wind pressure of the train rendezvous has less influence on the derailment coefficient of the vehicle, wheel load reduction ratio, vertical acceleration of the vehicle body and vertical Sperling, but on the wheel-rail lateral force, lateral force of the axle, lateral acceleration of the vehicle body, lateral Sperling and The impact of dynamic offset are greater. With the increase of the intersection speed, the indicators of vehicles show an increasing trend;

(2) The influence of wind pressure on bridge displacement, impact coefficient and acceleration is weak, and the lateral impact on the bridge is greater than that on the vertical;

(3) As the intersection speed increases, the wheel load reduction rate, vehicle body lateral acceleration, lateral Sperling will exceed the existing specification limits. Taking the lateral acceleration of the vehicle body and the lateral Sperling as indicators, it is safer to control the speed of the two vehicles at a speed below 450km/h. Considering the high-speed intersection of trains on the bridge, the bridge vibration impact coefficient will be larger than the existing specifications, and the existing standard impact coefficient method will not apply.

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