Vehicle-train-bridge coupled vibration of the road-rail bridge

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Abstract—For the vehicle-bridge coupled vibration of road-rail bridge, the difference of the dynamic responses of the bridge between only considering the vehicle or train loads and considering the vehicle and train load together, needs to be studied. In this paper, taking the Binzhou road-rail steel truss bridge as an example, the motion equations of bridge, car and train are established respectively, through the interaction among the three subsystems, the three subsystems are coupled. The dynamic responses of the whole system only considering the vehicle or train loads and considering the vehicle and train load together are analyzed. The results show that the dynamic response under the vehicle and train loads is not a simple superposition of that under the vehicle or train load separately. And the peak dynamic responses at different positions doesn’t appear under one certain condition. Therefore, different conditions need to be considered when the road-rail bridge is designed.

1. Introduction
Refer to the research of vehicle-bridge coupled vibration [1], because of the larger load and the faster speed, the train-bridge coupled vibration was studied firstly. Relatively speaking, the vehicle-bridge coupled vibration of road bridge [2] was studied little. However, with the increasing load and traffic of the automobiles, the vibration of bridge structure caused by automobile loads becomes more and more serious. In a word, with the rapid development of highway and railway transportation, the vehicle-bridge coupled vibration of road bridge and railway bridge has been studied a lot [3-5], but the vehicle-bridge coupled vibration under the vehicle and train loads acting on the road-rail bridges is very few [6-10]. In this paper, Binzhou Yellow River Highway-railway bridge will be taken as an example, a coupled vibration model of the automobile-train-highway railway steel truss bridge is established. The coupled vibration of the automobile-bridge, the train-bridge and the automobile-train-bridge are analyzed separately. The analysis of the vibration results provides the basis of the bridge structure design of the highway-railway bridge.
2. The vehicle-bridge vibration model of highway-railway Steel Truss Bridge

2.1 The bridge model
In this paper, the steel truss bridge over the Yellow River in Binzhou area is studied. The length of the bridge is 780m, the height and the width of the truss are 18m and 11m separately, the 5 spans are 120m + 3×180m + 120m. The bridge model is built by ANSYS, the steel truss and the bearing are simulated by BEAM188 and COMBINE14 elements respectively. Fig. 1 shows the side view of 1/2 bridge structure and the corresponding road and railway pavement layout.

\[
\begin{bmatrix}
M_s
\end{bmatrix}\ddot{Z}_s + \begin{bmatrix}
C_s
\end{bmatrix}\dot{Z}_s + \begin{bmatrix}
K_s
\end{bmatrix}Z_s = \begin{bmatrix}
F_s
\end{bmatrix} \tag{1}
\]

where, \([M_s]\) is the overall mass matrix of the bridge structure; \([C_s]\) is the overall damping matrix of the bridge structure; \([K_s]\) is the overall stiffness matrix of the bridge structure; \([F_s]\) is the load vector of the bridge structure; \([\dot{Z}_s]\), \([Z_s]\), \([\ddot{Z}_s]\) are the acceleration, velocity and displacement vector of bridge structure nodes.

2.2 The train model
In this paper, the vertical train model with 10 degrees of freedom in reference 11 is used and shown in Fig.2.

Figure 2. Train model with 10 degrees of freedom.
2.3 The vehicle model
The vehicle model used in this paper includes a vehicle body and two wheelsets. The vehicle body has two degrees of freedom such as vertical displacement and rotation, and the wheelsets have only vertical displacement.

2.4 The motion equations of train or vehicle models
The motion equations of the vehicle or train can be obtained according to the above models, shown in Eq. 2.

\[ \left[ M \right] \ddot{Z} + \left[ C \right] \dot{Z} + \left[ K \right] Z = F \]  

Where, \([M]\), \([C]\) and \([K]\) are the mass, damping and stiffness matrix of the vehicle respectively, \(F\) is the load vector of the vehicle, \(\dot{Z}\), \(\ddot{Z}\) and \(Z\) are the acceleration, velocity and displacement vectors of the vehicles.

2.5 The coupling of the vehicle-train-bridge motion equations
Considering the interaction force between the vehicle and the bridge, the motion equations of bridge, vehicle and train are coupled simultaneously and programmed by Matlab software, and the dynamic response is solved by Newmark-β step by step integration method.

3. Comparative analysis of results under different load conditions
The speeds of the vehicle and the train are both taken as 60km/h, and the number of them is both one. The track irregularity and road surface irregularity are not considered. Three different conditions are analyzed. Case 1: one vehicle is running; Case 2: one train is running; Case 3: one vehicle and one train are passing at the same time.

Fig. 4 is the peak values of the dynamic responses of the mid-span nodes of the railway deck and the highway deck under different working conditions respectively. The specific locations of the nodes are shown in Fig. 1.

Figure 3. The peak dynamic responses of mid-span nodes on bridge deck

Fig. 3 show that: the displacement peak value of case 3 is almost equal to the summation of case 1 and case 2, it means the peak displacement basically fits the superposition relation; the peak velocity
doesn’t accord with the superposition relation, the dynamic responses of case 2 and case 3 are close, it
means the influence of railway load on the velocity response is greater. The acceleration peak value
(except the No. 1 node) in case 3 is smaller than that in case 2 and larger than that in case 1, therefore,
there is no obvious relationship of the peak acceleration in three cases. In a word, in order to study the
dynamic response of bridge structure under the vehicle and train, it is necessary to build the model
including the vehicle and the train at the same time, and the latter two cases should both be considered.

Fig. 4 shows the acceleration time history curves of the train body under case 2 and case 3. Fig. 5
shows the vertical acceleration time history curves of the car body under cases 1 and 3. Fig. 6 shows the
rotation time-history curves of the degrees of freedom of the car body under cases 1 and 3; Fig. 7 is the
time-history curves of the wheel-rail interaction forces of the first wheel set of the train in cases 2 and 3.

![Figure 4. The acceleration time history curve of train body](image)

![Figure 5. The acceleration time history curve of car body](image)

![Figure 6. The angle displacement time history curves of car body](image)

![Figure 7. The force time history curves of 1# wheel of train](image)

Fig. 4, Fig. 5, Fig. 6 and Fig. 7 show that, comparing to case 1 and case 2, the vertical acceleration
of the car or train body, the rotation angle of the car body and the interaction force between the wheels
and the tracks of the first wheelset of the train in case 3 all increase. It can be seen that without
considering the track irregularity, the mutual influence between the car and the train is relatively small.

The displacement time history curves of the No.1, No.3 and No.5 nodes in case 3 are shown in Fig.
8. The acceleration time history curves of the No. 5 node in all three cases are compared in Fig. 9.
Fig. 8 shows that, the displacement peaks of No. 1, No. 3 and No. 5 nodes all appear when the dynamic load acts on its own span, when the dynamic load acts on other spans, the displacement of this span is very small, it means that the dynamic load mainly affects the displacement of the span it acting on, and hardly affects the displacement of other spans. Fig. 9 shows that the acceleration time history curves of bridge structures in different cases are quite different, especially in case 2 and 3 which include train loads, the vibration is quite strong, therefore, the train load should be the main dynamic load to be considered in the bridge structural design.

4. Conclusions
The dynamic response when vehicles and trains acting on the bridge structure together is not the sum of that when vehicles or trains acting on the bridge respectively. It’s not sure that the dynamic response peaks of the bridge structure, vehicles and trains appear in any cases. In order to analyze this kind of bridge structure more accurately, it is necessary to establish the vehicle-bridge coupling vibration model under several different working conditions, the design should be based on the envelope results.

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