Influence of Pier Heights on Spatial Vibration of the Train-Bridge System

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ABSTRACT
To investigate the spatial vibration of the train-bridge system, four multi-span simply supported beam bridge models with different pier heights are established, then the train-track-bridge coupling system is used to analyse the dynamic responses of the bridges as well as the trains. The following conclusions can be drawn: the frequency of a typical mode shape of the bridge decreases as the pier height ascends. The dynamic coefficient in the midspan is larger when the pier is higher, while this is not obvious when the train speed is below 350km/h. The lateral responses in the midspan are more sensitive to the change of pier height, and the displacements in the pier top show obvious distinction among different pier heights. The type of train, operation condition of train and train speed all have impacts on the vibration of the bridge. Compared with the bridge, responses of the vehicle show coherence among different pier heights, which illustrates that the pier height has less effect on the vibration of the train.

KEYWORDS: Spatial vibration; simply supported beam; pier height; train-track-bridge system; dynamic response; midspan; pier top.

1 INTRODUCTION
With the rapid development and demand of high-speed train in China, the construction of railway bridges in plains and mountains is underway. The multi-span simply supported beam bridge (Figure 1) is a common type of bridge in cities and outskirts, and its pier height changes variously due to the complexity of the terrain. Because the dynamic characteristics of simply supported beam bridge with different pier heights are different, the spatial coupling vibration of the train-bridge system is worthy of studying.

Figure 1: Multi-Span Simply Supported Beam Bridge
Researchers at home and abroad have done multiple studies about the train-bridge coupling vibration system, and a variety of outcomes were achieved. Savin (2001) analysed the vibration of simply supported beam under the impact of successive moving loads. Garinei et al. (2008) analysed the vibration of small and medium span railway bridges under high speed trains. Omlos et al. (2013) studied the lateral response of a high pier viaduct under the ICE-3 train. Li et al. (2013) analysed the dynamic characteristics of a suspension bridge and vehicles when two trains passing each other under crosswind. Wang et al. (2015) and Chen et al. (2015) studied the running safety of vehicles passing the bridge tower and wind barrier region, respectively. Yang et al. (2017) studied the resonance of trains and bridges using analytical and finite element approaches. Olmos et al. (2018) used the vehicle-bridge-wind interaction model to assess the running safety of TGV trains over a high-pier viaduct under crosswind.

In this paper, four multi-span simply supported beam bridge models with different heights of piers are established, where the spatial vibrations of the bridges and the trains are analysed based on the train-track-bridge system.

2 ENGINEERING BACKGROUND
2.1 An Overview of the Bridge Model

The bridge to study is located in the Yancheng-Nantong railway, with more than one hundred spans of simply supported beams. The structures of the beams and piers are shown in Figure 2 and 3, respectively. The main materials of the beam and pier are C50 and C30 reinforced concretes, respectively. The length of the box girder is 32.6m, with a 0.1m gap between two girders. The height and width of the box girder is 2.8m and 12.6m, respectively. In order to simplify the analysing model, four 9-pier and 8-beam bridges with different pier heights are taken into account (Figure 4), where the pier top represents the top of pier 5#, and the midspan represents the middle of the box girder on pier 4# and 5#. Two types of trains (CRH3 and CRH380) are considered in this paper, each has 16 carriages.

![Figure 2: Structural Diagrams of the Beam (Unit: mm)](image)

(a) Vertical Profile of the Box Girder on Pier Top  
(b) Cross Section in the Midspan of the Box Girder

Figure 2: Structural Diagrams of the Beam (Unit: mm)

![Figure 3: Schematic Diagram of Pier (Unit: cm, Where H Represents Pier Height)](image)

Figure 3: Schematic Diagram of Pier (Unit: cm, Where H Represents Pier Height)

![Figure 4: Overall Bridge Layout](image)

Figure 4: Overall Bridge Layout
The foundation stiffness at the bottom of pier is considered, where the horizontal force and bending moment stiffness in longitudinal and transverse directions is shown in Table 1. There are two lanes of non-ballasted track on the box girder with a distance of 5m, and the transverse and longitudinal irregularities are derived from the German high-speed track spectrum.

Table 1 Foundation Stiffness at the Bottom of Pier

<table>
<thead>
<tr>
<th></th>
<th>Longitudinal Horizontal Force</th>
<th>Longitudinal Bending Moment</th>
<th>Transverse Horizontal Force</th>
<th>Transverse Bending Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>kN/m</td>
<td>kN·m/rad</td>
<td>kN/m</td>
<td>kN·m/rad</td>
</tr>
<tr>
<td>Value</td>
<td>7.694×10³</td>
<td>4.734×10³</td>
<td>7.547×10³</td>
<td>1.199×10³</td>
</tr>
</tbody>
</table>

Based on the interaction between wheel and rail, track and bridge, the train-track-bridge spatial coupling system is established (Li et al., 2018), as shown in Eqs. (1) - (3) below. Based on the train-track-bridge theory, a self-developed train-track-bridge system solver BDAP is compiled, and the numerical integration methods are adopted to solve the system.

\[
M_b \ddot{x}_b + C_b \dot{x}_b + K_b x_b = F_{ib} \tag{1}
\]

\[
M_t \ddot{x}_t + C_t \dot{x}_t + K_t x_t = F_{it} + F_{vt} \tag{2}
\]

\[
M_v \ddot{x}_v + C_v \dot{x}_v + K_v x_v = F_{iv} \tag{3}
\]

In the equations above, subscripts \( b \), \( t \) and \( v \) represent the bridge, track and train respectively. Matrixes \( M \), \( C \) and \( K \) represent the generalized mass, damping and stiffness respectively. Vectors \( \ddot{x} \), \( \dot{x} \) and \( x \) represent the acceleration, velocity and displacement respectively. Vectors \( F_{ib} \) and \( F_{it} \) represent the interaction forces between bridge and track. Vectors \( F_{iv} \) and \( F_{iv} \) represent the interaction forces between track and train.

2.2 Dynamic Analysis of the Bridge

Figure 5 and Table 2 show the typical mode frequencies and shapes of the bridge, where five different pier heights (0m, 5m, 10m, 15m, 20m) are considered. It is easy to observe that the longitudinal floating frequency is the lowest with any pier height, and the frequency of any mode shape decreases as the pier height increases.

Table 2 Typical Mode Shapes of the Bridge
3 DYNAMIC RESPONSES OF THE BRIDGE

3.1 Dynamic Coefficients of the Bridge Midspan

In this section, the dynamic coefficients in the midspan result from a CRH3 or CRH380 train running at different speeds are shown in Figure 6. With the increase of train speed, the dynamic coefficients show a tendency to magnify in all cases, and they grow slowly under 350km/h but rapidly above it. The dynamic coefficients at the train speed of 250km/h are nearly the same, while they separate into two groups above it due to the type of train, where the dynamic coefficients at any speed of CRH3 are slightly higher than those of CRH380. The difference of dynamic coefficients caused by pier height is obvious at 420km/h, and the dynamic coefficient is larger when the pier is higher.

3.2 Dynamic Responses of the Bridge Midspan

The displacement and acceleration responses in the midspan under a CRH380 train (420km/h) are shown in Figure 7. The lateral displacement is larger as the pier height grows, while the lateral acceleration is larger as the pier height shortens. The lateral displacement in the mispan can be 0.6mm when the pier height is 20m, while it decreases to only 0.1mm when the pier height is 5m. The vertical displacement and acceleration are nearly the same among four heights of piers. In all cases above, the maximum deflection is 2.5mm, and the vertical acceleration reaches 1.5m/s².
### 3.3 Dynamic Responses of the Bridge Pier Top

The maximum values of responses in the pier top under a CRH380 train at different train speeds are shown in Figure 8. The differences of displacements among four pier heights are clear, and the displacements in two directions all grow larger at any train speed as the pier height increases. When the train speed is above 375 km/h, the vertical displacement grows faster. The vertical acceleration shows a tendency to grow as the train speed increases, while the change of lateral acceleration is inconsistent among different pier heights.
3.4 Summaries of Bridge Dynamic Responses under Different Modes of Train

In this section, 8 different cases of loading modes of train are shown in Table 1, where the type of train (CRH3 or CRH380), operation condition (single or double), and operation speed (250~350km/h or 375~420km/h) are all taken into consideration. The single operation means only one of the tracks is loaded, while the double operation means both of the tracks are loaded.

Table 3 Loading Modes of the Train

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of Train</th>
<th>Operation Condition</th>
<th>Operation Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>CRH3</td>
<td>Single</td>
<td>250~350km/h</td>
</tr>
<tr>
<td>②</td>
<td>CRH3</td>
<td>Single</td>
<td>375~420km/h</td>
</tr>
<tr>
<td>③</td>
<td>CRH380</td>
<td>Single</td>
<td>250~350km/h</td>
</tr>
<tr>
<td>④</td>
<td>CRH380</td>
<td>Single</td>
<td>375~420km/h</td>
</tr>
<tr>
<td>⑤</td>
<td>CRH3</td>
<td>Double</td>
<td>250~350km/h</td>
</tr>
<tr>
<td>⑥</td>
<td>CRH3</td>
<td>Double</td>
<td>375~420km/h</td>
</tr>
<tr>
<td>⑦</td>
<td>CRH380</td>
<td>Double</td>
<td>250~350km/h</td>
</tr>
<tr>
<td>⑧</td>
<td>CRH380</td>
<td>Double</td>
<td>375~420km/h</td>
</tr>
</tbody>
</table>

The maximum values of displacement and acceleration in different positions (midspan or pier top) and directions (vertical or lateral) of the bridges with four heights of piers are shown in Figure 9. The vertical responses in the midspan are the largest in nearly all cases, where the maximal displacement and acceleration are 5.2mm and 3.7m/s² respectively. The lateral displacements in the pier top and midspan are almost identical in each case, while the lateral accelerations in the pier top and midspan vary in the same case. The vertical displacements in the pier top as well as the lateral accelerations in the midspan are the minimum in any case. The vertical responses of the bridge under the single-lane train are lower than those of the double-lane train, while the lateral responses are somewhat different.

Figure 9: Maximum Values of Bridge Dynamic Responses under Different Loading Modes

4 DYNAMIC RESPONSES OF THE TRAIN

4.1 Dynamic Responses of the Train at a Steady Speed

Figure 10 shows the time-history responses of a CRH380 vehicle at the speed of 420km/h. It is easy to observe that the vertical responses and lateral displacement of the train are the same among four pier heights, whereas the lateral displacement shows some difference. The maximal lateral displacement is 2.2mm when the pier height is 20m, while it decreases a little bit to 1.9mm when the
pier height is shortened to 5m. This phenomenon shows that the pier height has less impact on the vehicle than the bridge.

Figure 10: Time-History Curves of Dynamic Responses in CRH380 Train at a Speed of 420km/h

4.2 Running Safety and Riding Comfort Indexes of the Train

The running safety (lateral axle force and derailment coefficient) as well as the riding comfort (lateral and vertical Sperling) indexes of a CRH380 train are shown in Figure 11. Each index grows larger as the train speed increases, where the running safety indexes show a steady growth from 250km/h to 420km/h, while the riding comfort indexes show a relatively rapid growth from 250km/h to 300km/h. The difference among four pier heights is not clear, which means that the influence of pier heights can be neglected when analyzing the safety of train over simply supported beam bridges.
5 CONCLUSIONS

(1) The frequency of a typical mode shape of the bridge ascends as the pier height decreases. (2) The dynamic coefficients in the midspan vary with the pier height at higher train speeds. (3) Compared with vertical responses, the lateral responses in the midspan show more differences among the four pier heights. (4) The displacements in the pier top are larger when the pier is higher, and the vertical accelerations in the pier top all enlarge as the train speed increases. (5) The speed, type and operation condition of the train all influence the vibration characteristics of the bridge. (6) The changes of the train responses are less prominent among four pier heights than responses of the bridge.

REFERENCES