Study on the Coupling Vibration and Driving Comfort of the Railway and Highway Bi-purpose Bridge

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Abstract. In this paper, the influence of the track irregularity, speed and vehicle grouping on the dynamic respond and driving comfort of the bridge is studied. The results show that, the interaction between the automobile and the train can be effectively reduced by increasing the damping of the bridge structure; it's the span and the train formation but not the speed and the track irregularity which effect the dynamic displacement of the bridge; the driving comfort is influenced a lot by the track irregularity. This study is of great significance to the driving comfort.

1. Introduction

Due to the complex structure of the highway and railway dual-use bridge, the interaction between the bridge, the cars and the trains is also more complicated. Many researchers have studied about building the spatial coupling model of the vehicle and the bridge[1~3], considering the track irregularity and the bridge surface roughness[4,5] and so on, but seldom researchers studied the vehicle-bridge coupling vibration of the highway and railway dual-use bridge. Therefore, in this paper, taking the Binzhou Yellow River dual-use bridge as an example, the cars-bridge-train coupling vibration model is founded, and the influence of many factors on dynamic response and driving comfort is studied.

2. The model of the car-bridge-train coupling vibration system

2.1. Introduction of Binzhou Yellow River dual-use bridge

Figure 1. The half structure of the bridge.
The length of Binzhou Yellow River dual-use bridge is 780m, the 5 spans of this continuous steel truss beams are 120m+3×180m+120m separately, the height is 18m and the width of the truss is 11m. The figure of the half bridge structure is shown in Figure 1. The node numbers of the following dynamic analysis show in this figure. The finite-element model of this bridge is established by ANSYS software. The steel pole of the truss is simulated by BEAM188 element, the support is simulated by COMBINE14 and the constant loads are simplified as the mass block.

2.2. Dynamic characteristics analysis of the bridge
The self-vibration analysis, which can verify if the mass matrix and stiffness matrix are correct, is the basis of the following dynamic analysis [6]. And according to the previous researches [7], the dynamic response is mainly effected by the front modes of the bridge structure. According to the modal analysis of the bridge structure, the natural frequencies of the front 5 modes are listed in Table 1. And the front 5 vibration modes are shown in Figure 2.

| Mode | Frequency (Hz) |
|------|---------------|
| 1    | 0.534 75      |
| 2    | 0.612 63      |
| 3    | 0.681 00      |
| 4    | 0.711 85      |
| 5    | 0.848 68      |

![Table 1. Natural frequency.](image)

(a) The 1st mode  
(b) The 2nd mode  
(c) The 3rd mode  
(d) The 4th mode  
(e) The 5th mode  

Figure 2. The front 5 vibration modes.

2.3. The vehicle model
According to the reference [8], the train body, the wheels and the bogies are simulated by MASS21 element, the springs and the damping between the body, the bogies and the wheels are simulated by COMBIN 14 element. The car model has 4 degrees of freedom and train model has 10 degrees of freedom. The finite-element model is shown in Figure 3. In the following analysis, the parameters of the car and train are both adopted in reference [9].
3. The influence of the different factors on the coupling vibration of the car-bridge-train system

3.1. The track irregularity

The speeds of the car and the train are both 60km/h. The effect of no-irregularity, level-6 irregularity and level-5 irregularity on the car-bridge-train is analysed. The Fourier transform method \cite{10,11} is adopted to simulate the track irregularity by Matlab programs. The time-history curves of the vertical acceleration of the car and train body are shown in Figure 4 and Figure 6, the time-history curves of the interaction forces between the 1st wheel and the road surface or the rail are shown in Figure 5 and Figure 7.

Figure 4–7 show that, the track irregularity has little effect on the dynamic response of the car but has significant effect on that of the train. The main reason is that the track irregularity can influence the train directly, however the vibration is reduced a lot during the transfer to the road surface, therefore, the dynamic response of the car is influenced little. As a result, to reduce the effect of the train on the car, it’s an effective method to increase the damping of the bridge. Figure 4 also shows that, the wheel-rail interaction force is always up or down the balance, this result also proves that the analysis is correct.
Figure 6. The time-history cures of the vertical acceleration of the car.

Figure 7. The time-history curves of the interaction forces between the 1st wheel and the rail.

The vehicle comfort levels of different irregularities are shown in Table 2. The table shows that, the stability indicators change a lot with the increasing of the irregularity level. Therefore, it’s very useful for improving the ride comfort by the improvement of the track stability.

Table 2. The vehicle comfort levels of different irregularities.

| The level of the irregularity | The stability indicator(w) | The comfort level |
|------------------------------|-----------------------------|-------------------|
| No irregularity              | 0.6738                      | excellent         |
| Level-6 irregularity         | 0.9643                      | excellent         |
| Level-5 irregularity         | 1.1915                      | excellent         |

The Sperling stability indicator is adopted [12],

\[
W = 7.08 \left[ \frac{A^2}{f} F(f) \right]^{0.1}
\]  

In which, \(W\) is the stability indicator; \(A\) is the acceleration of the vehicle body, \(g\); \(f\) is the frequency, Hz; \(F(f)\) is the correction factor of the frequency.

3.2. The train speed

Table 3. The node peak displacement of the bridge under different train speed.

| Node | 60 km/h | 70 km/h | 90 km/h | 105 km/h | 120 km/h |
|------|---------|---------|---------|----------|----------|
| 1    | 10.689  | 9.841   | 9.663   | 10.614   | 10.074   |
| 3    | 14.589  | 12.927  | 11.056  | 11.438   | 12.226   |
| 5    | 14.42   | 10.673  | 8.259   | 8.278    | 11.858   |
| 7    | 10.766  | 10.109  | 9.895   | 11.095   | 10.033   |
| 9    | 14.279  | 12.607  | 11.045  | 10.313   | 10.577   |
| 11   | 10.107  | 10.538  | 8.006   | 7.776    | 9.002    |

The car speed is 60km/h, the track irregularity is level 6, the road irregularity is not considered, the train speeds are 60, 75, 90, 105, 120km/h. In the 5 different conditions, the node peak displacement of the bridge and the impact factors are shown in Table 3 and Table 4, and the vehicle comfort levels are shown in Table 5.

Table 3 and 4 show that, the displacement of all nodes and the impact factors change little with the train speed; under the same speed, the displacements of number 3,5,9,11 nodes are much larger than that of other node, because these nodes are related to the large spans. Table 5 shows that, the train speed has little effect on the driving comfort.
Table 4. The impact factors under different train speed.

| Node | 60 km/h | 70 km/h | 90 km/h | 105 km/h | 120 km/h |
|------|---------|---------|---------|----------|----------|
| 1    | 0.268   | 0.168   | 0.147   | 0.260    | 0.195    |
| 3    | 0.174   | 0.040   | -0.110  | -0.079   | -0.016   |
| 5    | 0.156   | -0.144  | -0.338  | -0.336   | -0.049   |
| 7    | 0.235   | 0.160   | 0.135   | 0.273    | 0.151    |
| 9    | 0.161   | 0.025   | -0.102  | -0.161   | -0.140   |
| 11   | 0.143   | -0.146  | -0.351  | -0.370   | -0.271   |

Table 5. The level of driving comfort under different train speed.

| Speed (km/h) | Stable indicator ($) | Comfort level |
|--------------|----------------------|---------------|
| 60           | 0.964 3              | excellent     |
| 70           | 1.013 0              | excellent     |
| 90           | 1.015 4              | excellent     |
| 105          | 1.029 1              | excellent     |
| 120          | 1.168 5              | excellent     |

3.3. The different train formations

In the following analysis, the speed of the car and the train are both 60km/h, the track irregularity and the road pavement irregularity are not considered, and one car is moving. The train formations are 1, 3 and 5 carriages separately. Under different train formations, the peak displacements of several nodes are shown in Table 6, and the driving comfort levels are shown in Table 7.

Table 6. The peak displacements of several nodes under different train formations.

| Node | 1 carriage | 3 carriages | 5 carriages |
|------|------------|-------------|-------------|
| 1    | 10.687     | 13.185      | 13.269      |
| 3    | 14.307     | 20.629      | 22.316      |
| 5    | 14.334     | 20.428      | 21.066      |
| 7    | 10.780     | 13.143      | 13.309      |
| 9    | 14.009     | 20.237      | 22.206      |
| 11   | 14.025     | 20.114      | 20.870      |

Table 7. The driving comfort levels under different train formations.

| Carriage number | Stable indicator ($) | Comfort level |
|----------------|----------------------|---------------|
| 1              | 0.673 8              | excellent     |
| 3              | 0.652 2              | excellent     |
| 5              | 0.656 2              | excellent     |

Table 6 shows that, with the increasing of the train formation number, the displacements of the bridge change larger. Compared the displacements of No.1 and No.7, No.3 and No.9, No.5 and No.11, the displacements change little, therefore, this proves that the stiffness of the bridge is very large. Table 7 shows that, with the increasing of the train formation number, the driving comfort reduces firstly then increases.

4. Conclusions

In this paper, the finite-element model of the bridge and the multi-rigid-body models of the car and train are established by ANSYS software. These three sub-systems are coupled by constraint equations. The influence of the track irregularity, the train speed and the train formations on this system are studied. The results show that, the displacement of the bridge and the impact factors are mainly related to the bridge span and the train formations; the train speed and the track irregularity have little effect on the displacement of the same node; the train track has significant influence on the driving comfort, and the train formation can also cause the change of the driving comfort, it’s because that the vibration of the bridge has a lot influence on the train as the less load when the train formation number is small; with
the increasing of the train formation, the load on bridge increases, the vibration of the train caused by the vibration of the bridge reduces; the driving comfort is influenced little by the train speed; the train load has little effect on the dynamic response of the car because of the structure damping. However, in this paper, only the track irregularity is considered. In the following research, other factors such as the road pavement roughness and the car load, also need to be considered.

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