Coupling Vibration Analysis and Comfort Evaluation of Passenger-Vehicle-Bridge System

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Abstract. Based on a continuous box girder bridge on Beijing Metro Line 5, a coupling vibration model of passenger-vehicle-bridge is established. According to the Lagrange equation, the differential equations of motion of the system are derived. The corresponding calculation program is written in Fortran language to study the dynamic response of passengers, vehicles and bridges. The difference between passenger and vehicle vibration responses are compared and then the passenger comfort is evaluated. The bridge is subjected to on-site vibration testing, and the measured data is used to verify the reliability of the calculation model. The results show that the numerical calculation results are consistent with the vibration change tendency of the measured data, and the amplitudes are relatively close. The established dynamic analysis model and calculation program have good reliability; the passenger's partial vibration response is different from the vehicle and has a certain hysteresis. According to the ISO2631 standard, the riding comfort level of the section is uncomfortable at part of the driving speed, and the passenger's comfort may be the worst at the middle position.

1. Introduction

With the rapid development of Chinese high-speed railway and rail transit and its advantages of safety, efficiency, punctuality and environmental protection, more and more people have used it as the preferred travel tool. At present, experts and scholars at home and abroad have conducted in-depth research on the safety of trains. Many research results in special conditions such as strong crosswind, earthquake action, frost heave in cold regions and uneven settlement of foundation have been successfully transformed, which effectively ensures the safety of train operation [1-2]. However, in the context of security assurance, passenger comfort issues are becoming more and more obvious, and have gradually become the focus of the railway departments [3-4].

The motion state of the rolling stock, the noise, the temperature and humidity inside the cabin, the lighting conditions inside the vehicle, and the physical condition of the passenger all affect ride comfort. Among them, vehicle vibration has a great influence on passenger comfort, especially when the vehicle passes through the bridge. At present, some scholars have established a human sitting posture model with multiple degrees of freedom, and combined with the vehicle or bridge to form a passenger-vehicle coupling model [5-8], a passenger-seat coupling model [9-10], and a passenger-vehicle-bridge coupling model [11-12], and then evaluate the ride comfort according to the ISO2631-1 standard. It is generally
concluded that simply using the vibration response of the vehicle to characterize the human vibration will overestimate the passenger's comfort level. The above literature considers the dynamic interaction between passengers and vehicles, and more realistically reflects the passenger's vibration response, but most of the research focuses on vehicle design, and the incentive effect of bridge structure vibration is not yet perfect.

Based on the research status of vehicle-bridge coupling vibration and the riding comfort, this paper establishes a passenger-vehicle-bridge coupling vibration model considering the dynamic interaction between passengers and vehicles, and calculates the vibration response of each part, and adopts ISO2631 standard to evaluate the riding comfort.

2. Vibration model of the passenger-vehicle-bridge coupling system

It can be seen from the above literature that the evaluation of vibration comfort should be based on passengers, and it is more reasonable to analyze the vibration response of passengers. Therefore, considering the track irregularity, a passenger-vehicle-bridge coupling model is established, as shown in Figure 1.

![Figure 1. Coupling vibration analysis model of passenger-vehicle-bridge system](image)

Among them, the passenger considers the model in the form of sitting posture shown in Figure 2. Each carriage is equivalently considered to have 10 rows of passengers, and each row of passengers has 6 degrees of freedom, which are yaw $Y_m$, sinking $Z_m$, telescopic $X_m$, rolling $\theta_m$, Shake head $\varphi_m$ and nod $\psi_m$. The vehicle model is a multi-degree-of-freedom vibration system composed of a carriage, two bogies, four wheelsets and some spring-damper suspensions, as shown in Figure 3. In this paper, a subway B1 train consisting of 6 cars is used. The $i$-th car considers five degrees of freedom, such as yaw $Y_{ci}$, sinking $Z_{ci}$, rolling $\theta_{ci}$, Shake head $\varphi_{ci}$ and nod $\psi_{ci}$, etc. The $j$-th bogie considers five degrees of freedom such as yaw $Y_{bi}$, sinking $Z_{bi}$, rolling $\theta_{bi}$, Shake head $\varphi_{bi}$ and nod $\psi_{bi}$, etc. The $l$-th wheel pair considers the degrees of freedom of the yaw $Y_{li}$, the ups and downs $Z_{li}$, and the roll $\theta_{li}$ direction. Therefore each vehicle has 27 degrees of freedom.

![Figure 2  Passengers’ vibration model](image)

![Figure 3  Vehicle model and parameters](image)

According to Lagrange equation, the motion equation of the system is deduced and obtained.

$$\begin{bmatrix} M_{pp} & 0 & 0 \\ 0 & M_{vv} & 0 \\ 0 & 0 & M_{bb} \end{bmatrix} \begin{bmatrix} \ddot{R}_p \\ \ddot{R}_v \\ \ddot{R}_b \end{bmatrix} + \begin{bmatrix} C_{pp} & C_{pv} & 0 \\ C_{vp} & C_{vv} & C_{vb} \\ 0 & C_{bv} & C_{bb} \end{bmatrix} \begin{bmatrix} \dot{R}_p \\ \dot{R}_v \\ \dot{R}_b \end{bmatrix} + \begin{bmatrix} K_{pp} & K_{pv} & 0 \\ K_{vp} & K_{vv} & K_{vb} \\ 0 & K_{bv} & K_{bb} \end{bmatrix} \begin{bmatrix} R_p \\ R_v \\ R_b \end{bmatrix} = \begin{bmatrix} F_p \\ F_v \\ F_b \end{bmatrix}$$ (1)
In the equation, the lower corners "p", "v", "b" represent passengers, vehicles and bridges respectively, M, C, K respectively mass, damping, stiffness matrix, R is the displacement vector, and F is the external force acting on the vehicle.

Displacement vector of passengers in the i-th carriage can be expressed as
\[ \mathbf{R}_i = [R_{i1} \ R_{i2} \ \cdots \ R_{in} \ \cdots \ R_{in}]^T \]  \hspace{1cm} (2)

The displacement vector of the n-th row of passengers can be expressed as
\[ \mathbf{R}_{in} = [X_{in} \ Y_{in} \ Z_{in} \ \theta_{in} \ \varphi_{in} \ \psi_{in}]^T \]  \hspace{1cm} (3)

Vehicle displacement vector can be expressed as
\[ \mathbf{R}_{vi} = [R_{ci} \ R_{ti} \ R_{oi}]^T \]  \hspace{1cm} (4)

External force acting on the i-th car can be expressed as
\[ \mathbf{F}_{vi} = [F_{ci} \ F_{ti} \ F_{oi}]^T \]  \hspace{1cm} (5)

For the above equations of time-varying coefficients, the integral iterative solution is solved by Newmark-β algorithm, and the corresponding calculation program is written by Fortran to study the vibration response of each part of the system during the bridge passing through the bridge.

3. Case study
A three-span continuous box girder bridge of Beijing Metro Line 5 is selected as the research object, as shown in Figure 4, and the three-dimensional model of the bridge is established by the finite element software MIDAS, as shown in Figure 5. By observing the speed of the train passing through the three-span continuous box girder bridge, which is maintained at 71-75 km/h, this paper chooses 70 km/h as the calculating speed.

Figure 4 Concrete continuous box girder bridge  Figure 5 Midas model

The field experiment layout and test equipment are shown in Figure 6-7. The horizontal and vertical acceleration of the side span is monitored by the TCZ-1A acceleration frequency sensor with an accuracy of 10-3 g, a range of ±2 g, and a sampling frequency of 100 Hz. The mid-span deflection adopts BJQN-V2.0 (non-contact) multi-point dynamic intelligent detection system with an accuracy of ±0.02mm, detection distance of 0.1m~500m, resolution of 0.01pix, and sampling frequency of 100Hz.
3.1. Bridge vibration response

Affected by the site and experimental equipment, the lateral displacement of the bridge span is too small to measure, and the measured vertical acceleration data is not ideal. Therefore, the measured deflection time history curve is plotted in Figure 8, and the simulated deflection time history curve is plotted in Figure 9; The measured lateral acceleration time history curve is shown in Figure 10, the simulated acceleration time history curve is shown in Figure 11.

Comparing Figure 8 with Figure 9 and Figure 10 with Figure 11, it can be seen that for the continuous box girder bridge, the measured data and the simulated calculation data are basically consistent, which both conform to the dynamic loading phenomenon in reality. The peak value of each data is close, the
measured dynamic deflection peak is 5.5mm, and the simulated dynamic deflection is 4.2mm. The main reason for the analysis is that during the measurement process, the measured value is too large due to the wind load and the large ground vibration caused by passing the vehicle. The measured data can verify the correctness of the simulation calculation model and program. The peak value of the measured mid-span acceleration is 4.1cm/s$^2$, and the peak value of the simulated mid-span acceleration is 3.7cm/s$^2$. The main reason for the analysis is that there are large vehicles passing through the main roads on both sides of the bridge and other vibration sources, which make the measured results larger. In addition, the simplification of finite element modeling will also have a certain impact on the calculation results. Therefore, the validity of the measured data and the reliability of the simulation model can be verified.

3.2. Passenger and vehicle vibration response

Taking the 1st row of passengers in the 4th carriage as the object of analysis, the time history curve of the horizontal and vertical acceleration comparison between passengers and carriages is drawn in Figure 12. It can be seen from the figure that the lateral vibration acceleration amplitude of the passenger is slightly larger than the carriage, while the vertical vibration acceleration amplitude is significantly smaller than the car, and the vibration in both directions has a certain lag compared with the carriage. There is a certain difference in the vibration response between the two, and the lateral acceleration of the two parts is greater than the vertical acceleration. Therefore, some railway codes at home and abroad are not very strict with the acceleration of the floor of the car as the passenger comfort evaluation index.

4. Comfort evaluation

The international standard ISO 2631-1 evaluates the passenger comfort by combining the root mean square values of the weighted accelerations in different directions and comparing them with the standard vibration comfort level. This paper evaluates passenger comfort according to the standard.

Uniaxial weighted acceleration rms $a_{W}$ can be expressed as

$$a_{W} = \left[ \int_{0.5}^{\infty} \omega_{z}^2(f)G_{wi}(f) df \right]^{0.5}$$  \hspace{1cm} (6)

In the formula, $G_{wi}(f)$ is an accelerated self-power spectral density function of equal broadband, m$^2$/s$^2$ Hz, $\omega_{z}^2(f)$ is a frequency weighted function.

$$\omega_{z}(f) = \begin{cases} 
0.5 f^{1/2} & (0.9 < f < 4) \\
1.0 & (4 < f \leq 8) \\
8 / f & f > 8
\end{cases}$$  \hspace{1cm} (7)

(a) Vertical accelerate  \hspace{2cm} (b) Lateral accelerate

*Figure 12  Acceleration time-history Comparison between passenger and train*
The RMS value of weighted acceleration in different directions can be expressed as

\[
a_w = \left[ (1.4a_{w_x})^2 + (1.4a_{w_y})^2 + a_{w_z}^2 \right]^{0.5}
\]  

The calculation procedure for obtaining the root mean square value of the weighted acceleration in different directions from the acceleration signal value is as shown in Figure 13.

According to the standard vibration comfort level, each passenger in the 4th car is in an uncomfortable state, and the passenger’s vibration response may be a little severe, which may cause physical or psychological discomfort. It can be seen from the figure 12 that the weighted acceleration RMS value of the passenger in the middle of the compartment is the largest, indicating that the passenger feels the fastest change in the middle position of the car, and the riding comfort in the middle position may be the worst.

5. Conclusion

In this paper, the passenger-vehicle-bridge coupling vibration analysis model is established. The coupled vibration response of the system is studied by the combination of experimental test and numerical calculation. The conclusions are as follows:

(1) The vibration tendency of the passenger is consistent with the vibration of the train, and has a certain hysteresis, and the partial vibration response is larger than the vibration response of the vehicle.

(2) It can be seen from the simulation calculation that the passenger comfort level in the system is low, in an uncomfortable state, and the passenger’s riding comfort in the middle position of the car may be the worst. Therefore, it is necessary to use passengers as the research subject of ride comfort evaluation, and more detailed system coupled vibration research is needed.

This paper considers the impact of passenger vibration response on riding comfort. If the subway riding environment is comprehensively considered, the influence of noise, passenger flow and other factors will make the evaluation result more objective and comprehensive, and further research is needed.

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