Vibration Measurement and Analysis of High Speed Railway Based on Wavelet Analysis

Rui Song
College of Civil Engineering and Architecture, Nanchang Institute of Technology, Nanchang 330029, China
Email: 402690572@qq.com

Abstract. In order to better study the vibration characteristics of railway viaduct, field test and pulsation test are carried out for the bridge vibration caused by the operation of a high-speed railway train. The natural vibration frequency of the bridge is analyzed, and 1/3 octave analysis and wavelet analysis are carried out for the vibration signal caused by the train excitation. The analysis results show that: the measured value of vertical frequency of bridge is close to the theoretical value, and the measured value is slightly larger than the theoretical value; the wavelet analysis results show that the vibration energy of the measured points is mainly concentrated in the third frequency band (15.625 ~ 31.25 Hz), the fourth frequency band (31.25 ~ 62.5 Hz) and the seventh frequency band (250 ~ 500 Hz). Compared with the urban viaduct, the vibration and noise analysis of high-speed railway bridge should be appropriately extended to 500 Hz. The time-frequency diagram shows that the main vibration frequency range of the bridge is about 30-60 Hz.

Keywords. Rail transit, elevated box girder, bridge vibration, field test, 1/3 octave analysis, wavelet transform.

1. Introduction
In recent years, China's high-speed railway has been greatly developed. As of 2016, China's high-speed railway has formed a four vertical and four horizontal patterns, and will form an eight vertical and eight horizontal patterns in the future. In order to reduce the land requisition, improve the construction speed and reduce the settlement after construction, it is more and more widely to replace the road by bridge, and the proportion of bridge in the high-speed railway line is also increasing. The high-speed train acts on the bridge structure, which causes the vibration and noise of the bridge structure.

The existing analysis software can accurately analyze the vibration of bridge space structure. Considering the complexity of vehicle rail bridge coupling and the uncertainty of track irregularity and other parameters, field test method is still an important means to study structural vibration. It can provide important data validation for theoretical analysis and guide the determination of some important parameters. Zhang He et al. [1] conducted field test and numerical simulation on the vibration and noise of a simply supported steel bridge complained by residents, and compared and analyzed the influence of parameters such as pavement smoothness and vehicle calculation model.

Li Qi et al. [2] proposed a method to calculate the transient response of the structure by using the finite element method and modal superposition method, and the boundary element method to obtain the acoustic mode transfer vector of the bridge and multiply the frequency spectrum of the bridge modal coordinates to obtain the field point sound pressure. Li Xiaozhen et al. [3] took the 32m prestressed concrete simply supported box girder of high-speed railway as the research object, and
adopted the method of field hammer test to study the vibration transmission characteristics of railway concrete simply supported box girder. Wang Zijian et al. [4] carried out field test research, theoretical analysis and finite element simulation on single track simply supported box girder of Chengguan railway. Luo Wenjun et al. [5] established the track vibration simulation model by using FE-SEA hybrid method, and analyzed the influence of track random irregularity on the dynamic characteristics of bridge system. Li Zengguang et al. [6] established a vertical coupling model of vehicle track viaduct in frequency domain, and analyzed the vibration power flow and parameter influence transmitted to viaduct structure under wheel rail irregularity spectrum excitation through simulation calculation. Li Zhijun et al. [7] carried out field measurement on the internal vibration of five long-span bridges under different environments, and analyzed the influence of vehicle dynamic characteristics, bridge dynamic characteristics, deck roughness and vehicle speed on driving vibration based on the measured data. K. W. Ngai and C. F. ng [8] conducted vibration and noise tests on a concrete Viaduct on the west rail of Hong Kong. Xie Weiping [9] studied the vibration response of the track box girder for trains entering and leaving the station, taking Wuhan high-speed railway station as the research object, and compared with the theoretical analysis results. Liu Xijun et al. [10] took a double tower cable-stayed bridge model as the research object, and used continuous wavelet transform to study the time-frequency characteristics and energy distribution of the main beam vibration signal. The above research has accumulated a large amount of data, which is of great significance to the generation mechanism and influencing factors of bridge vibration and noise.

Most of the above studies are aimed at intercity railway bridges, which are relatively slow in running speed, and the cross-section form is quite different from that of high-speed railway bridges. The existing railway bridge vibration test signal analysis mainly focuses on the time domain and frequency domain analysis, which can’t reflect the energy distribution of bridge vibration in different frequency bands. In this paper, the vibration of a high-speed railway bridge is measured in the field. The measured maximum running speed of the train is 262 km/h, which is far higher than that of the general urban railway viaduct. According to the characteristics of bridge vibration signal, the basic method of energy distribution characteristic analysis is established by using the multi-resolution decomposition of wavelet transform and the basic relationship between layered reconstruction signal and original signal. The basic law of energy distribution of bridge vibration signal is obtained, which provides a certain reference for bridge vibration theory research and lays a foundation for the follow-up study of bridge structural noise.

2. Test Overview

2.1. Bridge Structure Form

The 32 m double track prestressed concrete simply supported box girder of a high-speed railway is selected in the test. The simplified section size is shown in figure 1. The standard span of the bridge is 32 m, the calculated span is 31.5 m, the design load is ZK live load, and the design speed is 350 km/h. The beam height at the center line of the bridge is 3.05 m, CRTs - II slab ballastless track is adopted, the rail type is 60 kg/m, the fastener is wj-8 fastener system, both ends of the bridge are plate rubber bearings, and the beam body is made of C55 concrete.

Figure 1. Cross section of box girder (unit: mm).
2.2. Test Scheme
The test site is located on a road directly below the railway bridge. Due to that it is a newly built suburban road with very small traffic flow, one side of the line is an existing railway, and the other side is relatively open without the influence of buildings and shrubs, which meets the requirements of acoustic test, so the relatively open side is selected for test and research. In order to ensure the accuracy of the test, the short-term closed traffic mode is adopted in the test process, and the existing lines and trains are avoided. The test site diagram is shown in figure 2, and figure 3 is the layout of measuring points on the mid span section of the bridge, in which V1-V4 is the vibration measuring point of the mid span section, and v5-v8 is the vibration measuring point of the 1/4 span section. The head recorder test system produced by American head company was used in the test. The acceleration sensor was made of pcb40ph. The concrete was ground flat and pasted with small steel plate at the test position, and the acceleration sensor was tightly pasted on the small steel plate. The sampling frequency is 10.24 kHz, which satisfies the Shannon sampling theorem. When the train passes the test bridge span, the Doppler velocimeter is used to measure the train passing speed, and the test instruments are calibrated before the test. Manual trigger mode is adopted to collect signals when the train approaches the test bridge span. The measured data are operating vehicles, and the train model is CRH3 power centralized EMU, which adopts 4-motor (m) and 4-trailer (T) marshalling mode.

3. Test Data Analysis
The test site is located on a road directly below the railway bridge. Due to that it is a newly built suburban road with very small traffic flow, one side of the line is an existing railway, and the other side is relatively open without the influence of buildings and shrubs, which meets the requirements of acoustic test, so the relatively open side is selected for test and research. In order to ensure the accuracy of the test, the short-term closed traffic mode is adopted in the test process, and the existing lines and trains are avoided. The test site diagram is shown in figure 2, and figure 3 is the layout of measuring points on the mid span section of the bridge, in which V1-V4 is the vibration measuring point of the mid span section, and v5-v8 is the vibration measuring point of the 1/4 span section. The head recorder test system produced by American head company was used in the test. The acceleration sensor was made of pcb40ph. The concrete was ground flat and pasted with small steel plate at the test position, and the acceleration sensor was tightly pasted on the small steel plate. The sampling frequency is 10.24 kHz, which satisfies the Shannon sampling theorem. When the train passes the test bridge span, the doppler velocimeter is used to measure the train passing speed, and the test instruments are calibrated before the test. Manual trigger mode is adopted to collect signals when the train approaches the test bridge span. The measured data are operating vehicles, and the train model is CRH3 power centralized EMU, which adopts 4-motor (m) and 4-trailer (T) marshalling mode. But the bottom plate is just opposite, because the roof bears the vertical train load, while the roof bears the bearing load, the two directions are opposite.
4. Wavelet Analysis
The Fourier transform is used to analyze the frequency spectrum of the signal, which can observe the characteristics of the signal from the time domain and frequency domain respectively, but can't combine the two organically. The wavelet transform can overcome the above shortcomings. In general, the lower time resolution can be used to improve the frequency resolution in the low frequency part (the signal is relatively stable), and the lower frequency resolution can be used in the high frequency part (the frequency changes little) for accurate time positioning. Therefore, wavelet can detect the transient in normal signal and display its frequency component [11]. Due to the limitation of space, this paper only selects the signals from the measurement points across the middle floor. The signal reconstruction results after seven levels decomposition with db8 wavelet are shown in figure 4. They correspond to eight frequency bands, and their frequency ranges are 0 ~ 7.8125 Hz, 7.8125 ~ 15.625 Hz, 15.625 ~ 31.25 Hz, 31.25 ~ 62.5 Hz, 62.5 ~ 125 Hz, 125 ~ 250 Hz, 250 ~ 500 Hz, 500 ~ 1000 Hz, respectively. The relative error between the original signal and the reconstructed signal is shown in figure 5. It can be seen from the figure that the error magnitude of the original signal and the reconstructed signal is 10^-8, which fully meets the requirements of engineering calculation and analysis accuracy.

The distribution of relative energy and peak vibration acceleration in different frequency bands obtained by the hierarchical reconstruction signal based on wavelet transform is shown in figure 6-7. In the ordinate of figure 7, EI represents the vibration energy of section I and E0 represents the total energy. It can be seen from the figure that the vibration signal energy is widely distributed in the frequency domain of 0-1000 Hz. The vibration energy and acceleration are the largest in the third frequency band (15.625 ~ 31.25 Hz), the fourth frequency band (31.25 ~ 62.5 Hz), and the seventh frequency band (250 ~ 500 Hz) The vibration acceleration also shows similar characteristics, which can't be obtained from time history curve and 1 / 3 octave frequency curve analysis, which reflects the originality of wavelet analysis method. Figure 8 is the time-frequency diagram of the vibration of the measuring point, and the color in the figure indicates the size of the wavelet coefficient modulus. It can be seen from the figure that in the whole driving time range, the main vibration frequency range of the bridge is concentrated in the range of about 30-60 Hz, which indicates that the vibration energy is the largest in this range, and some measures should be taken to reduce the energy in this range in the vibration reduction and noise reduction measures.

![Figure 4. Reconstructed signals of wavelet decomposition at different level.](image-url)
5. Conclusion
Through the pulsation test of different positions of railway bridge and vibration test under train load excitation, the test results are analyzed, and the following conclusions are obtained.

1) The maximum vibration acceleration of the plate from large to small is the top plate, the bottom plate and the web plate.

2) The $1/3$ octave curve of the four measuring points in the middle span shows that 50 Hz and 400 Hz are the common peak values of the three measuring points. 50 Hz is due to the maximum dynamic force of wheel rail, which leads to the maximum power transferred to the bridge. However, the source of 400 Hz peak needs further study.

3) The results show that the vibration energy of the mid span floor is concentrated in the third frequency band (15.625 ~ 31.25 Hz), the fourth frequency band (31.25 ~ 62.5 Hz) and the seventh frequency band (250 ~ 500 Hz). The energy of the bridge in the seventh frequency band is relatively large, which can’t be ignored. The existing research on vibration and noise of urban rail bridges is mainly concentrated within 200 Hz, so it is appropriate to extend the analysis frequency to 500 Hz for the vibration and noise research of high-speed railway box girder.

Acknowledgments
The study was supported by the Natural Science Foundation of Jiangxi education department (GJJ170984) and Natural Science Foundation of Jiangxi Province (20202BAB204027).

References
[1] Zhang H, Xie X and Yamashita M 2010 Analysis on low-frequency noise induced by vehicle bridge coupling vibration Journal of Vibration Engineering 23(5) 514-522.
[2] Li Q and Wu D J 2016 Numerical Simulation and Field Tests of Concrete Bridge-borne Low-frequency Noises *Journal of the China Railway Society* 33(12) 112-118.

[3] Li X Z, Song L Z and Zhang X 2016 Study on vibration transmission characteristics of high-speed railway simply-supported box-girders based on in-situ hammer excitation test *China Civil Engineering Journal* 49(5) 121-128.

[4] Wang Z J, Zhang X and Li X Z 2014 Vibration and structure-borne noise spectral characteristics of railway concrete box-girders *Chinese Journal of Applied Mechanics* 31(1) 85-91.

[5] Luo W J, Lei X L and Lian S L 2013 Analysis on Vibration of Ballastless Track-Bridge System Based on Hybrid FE-SEA Method *Journal of the China Railway Society* 38(8) 94-101.

[6] Li Z G and Wu T X 2013 Analysis of vibration power flow for a railway vehicle-track viaduct coupled system *Journal of Vibration and Shock* 29(11) 78-82, 93.

[7] Li Z J, Wu X C, Xu X L, et al. 2014 Vibration measurement and ride comfort analysis of a long span bridge *Journal of Vibration and Shock* 33(21) 213-217.

[8] Ngai K W and Ng C F 2002 Structure-borne noise and vibration of concrete box structure and rail viaduct *Journal of Vibration and Shock* 255(2) 281-297.

[9] Xie W P and Xu W 2012 Vehicle-induced vibration responses of a rail box girder in Wuhan station *Journal of Vibration and Shock* 31(8) 186-190.

[10] Liu X J, Xiang L J, Zhang S X, et al. 2015 Vibration Study of Bridges Effected by Vehicle Bumping Based on Wavelet Analysis *Journal of Vibration, Measurement & Diagnosis* 35(6) 1123-1128.

[11] Yan J W, Long Y, Fang X, et al. 2007 Analysis on features of energy distribution for blasting seismic wave based on wavelet transform *Explosion and Shock Waves* 27(5) 405-410.