Interaction and Multiscale Mechanics, Vol. 3, No. 4 (2010) 365-372
DOI: http://dx.doi.org/10.12989/imm.2010.3.4.365

Vibration simulation of a multi-story high-speed railway station

Mangmang Gao*[1], Jianzhen Xiong[1] and Zhaojun Xu[2]

[1]*Research & Development Center, China Academy of Railway Sciences, Beijing 100081, China*
[2]*Railway Engineering Research Institute, China Academy of Railway Sciences,Beijing 100081, China*

(Received September 3, 2010, Accepted October 22, 2010)

Abstract. Station is an important building in high-speed railway, and its vibration and noise may significantly affect the comfort of waiting passengers. A coupling vibration model for train-structure system is established to analyze and evaluate the vibration level of a typical waiting hall under dynamic train load. The motion of a four-axle vehicle with two suspension system is modeled in multi-body dynamics with linear springs and dampers employed. The station is modeled as a whole finite element structure which is 113 m in longitudinal and 163.5 m in lateral, and the stiffness of the station foundation is considered. According to the assumptions that both wheel and rail are rigid bodies and keep contact to each other in vertical direction, and the wheel/rail interaction and displacement coordination in horizontal direction is defined by the simplified Kalker creep theory, the vehicle spatial vibration model has 27 degrees-of-freedom. An overall analysis procedure is made of the train moving through the station, by which the dynamic responses of the train and the station are calculated. According to the comparison between analysis and test results, the actual connection status between different parts of the station is estimated and the vibration level of the waiting hall is evaluated.

Keywords: high-speed railway; station; moving train; vibration; evaluation.

1. Introduction

When a train travels on a bridge or a station, it will induce vibration of the structure and lead to a series of dynamic problems. Therefore, since the first railway line was built in England in 1825 and several railway bridges were destroyed by moving trains in Europe in middle of the 19th century, people have been studying the dynamic interaction between the train and the structures.

In the early stage of study, since the train speed was not high and computing ability was limited, the research on the train-bridge interaction was mainly focused on the vertical impact factor to provide a load amplification factor for the bridge static design (Adams and Bogy 1975). Since the occurrence of finite element method in 1960's, and an extensive use of computer and improvement in testing technology, powerful means has been provided and considerable progress obtained (Chu and Garg 1979, Shinozuka 1972). Now with the occurrence of high-speed trains and increase of span length of railway bridges, only impact factor can no longer meet the requirements of bridge

* Corresponding author, Professor, E-mail: gaomang@rails.com.cn

Fig. 1 The renderings of station

design. In order to ensure the safety and comfort of train, the research scope gradually extends to systematic and comprehensive direction, the train-track-structure system is studied and evaluation on different parts is estimated (Tanabe *et al*. 1987, Zhai 1996, Gao 2001, Yang 2008, Yau 2009), and then the influence of noise and vibration is examined (Xia 2005, Zhang *et al*. 2007).

Station is an important building in high-speed railway, which is rapidly developed in China, but its vibration and noise may significantly affect the comfort of waiting passengers. Up to the present, due to lack of corresponding control index, the noise and vibration reduction measures have not been adequately considered in design and construction of station. But recently, this situation has been changed, and systematic test and research process has been started. This paper is aimed to predict the dynamic responses of the vehicle-station interaction system, in which the multilayer station is analyzed as a whole structure. The main goal of the study is to evaluate the vibration level of waiting hall and platform layer, thus the possibility and effect of vibration control means can be estimated.

The station is located on a Chinese high-speed railway. It is built as a 3-story mixed structure of buildings and bridges: the upper story is the elevated over-crossing waiting hall, the middle story is platform, and the bottom story is exit hall. The ballastless high speed railway lines are on the middle story. In order to reduce the vibration of waiting hall, a 3-span continuous beam is designed as the support structure of the high-speed line and there is no direct connection between the bridge and the other parts of the station. The elevated waiting hall adopted steel truss and concrete slab to bear load. Shown in Fig. 1 are the renderings of the station.

The main content of simulation is to analyze the vibration response of the platform and waiting hall under passage of the train at a series of speeds between 200~350 km/h.

2. Train-station dynamic analysis model

2.1 Station model

The platform layer is composed of 10 continuous PC beams with spans of 30.9 + 49 + 30.9 m, and small platform beams are used to connect them. Among them, the main line bridge that supports high-speed track is totally separated from other ones which support arrival-departure tracks.

A steel truss is used in the equipment layer and station roof to bear load, and concrete slabs are used as the floors of platform layer and waiting hall.

The station is modeled as a three-dimensional finite element system which is 113 m in longitudinal and 163.5 m in lateral, the height between ground and roof is 46.89 m.

The station model uses uniform cross-section beam and shell element as basic elements. The beam element adopts two-joint space straight beam element with 12 degree-of-freedom, and each joint includes 3 linear displacements and 3 angular displacements. As for the shell element, rectangular plate element with 24 degree-of-freedom or triangular plate element with 18 degree-of-freedom is adopted. The element mass matrix adopted is uniform mass matrix. The Rayleigh damping is adopted for the structure, which can be expressed as

$$C = \alpha M + \beta K \tag{1}$$

where M and K represent the total mass matrix and stiffness matrix of the structure, respectively, and α and β are given as

$$\alpha = 2\omega_1\omega_2\frac{(\xi_2\omega_1 - \xi_1\omega_2)}{\omega_1^2 - \omega_2^2}$$

$$\beta = 2\frac{\xi_1\omega_1 - \xi_2\omega_2}{\omega_1^2 - \omega_2^2} \tag{2}$$

The damping ratio is taken as 2% for concrete structure, and 1% for steel structure.

The constraints of bearing between piers and beams or shells are disposed through master/slave joint, and the foundations of station are treated as fixed nodes.

The dead loads at different locations are processed with the self-weight of the elements into corresponding quality.

2.2 Vehicle model

The train model is composed of several EMUs (Electric Motor Units) and trailers. All rigid motions of vehicle elements are considered for defining the degrees-of-freedom: each car-body or bogie has 5 degree s-of-freedom respectively, including bounce, lateral, roll, pitch and yaw movements; Each wheel-set has 2 degrees-of-freedom as lateral and yaw movements. Thus for a 4-axle vehicle, each has 23 degrees-of-freedom, and for a 6-axle one, each has 27. See Fig. 3 for the vehicle computation model.

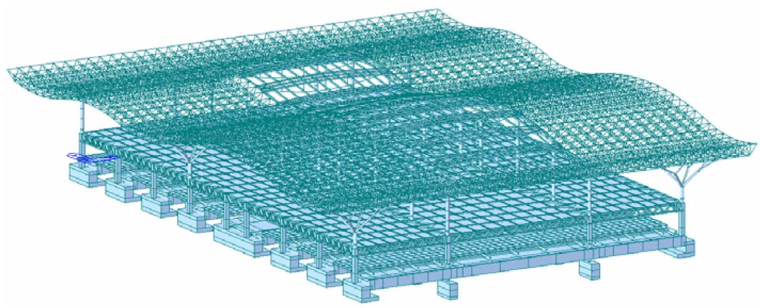


Fig. 2 Station dynamic analysis model

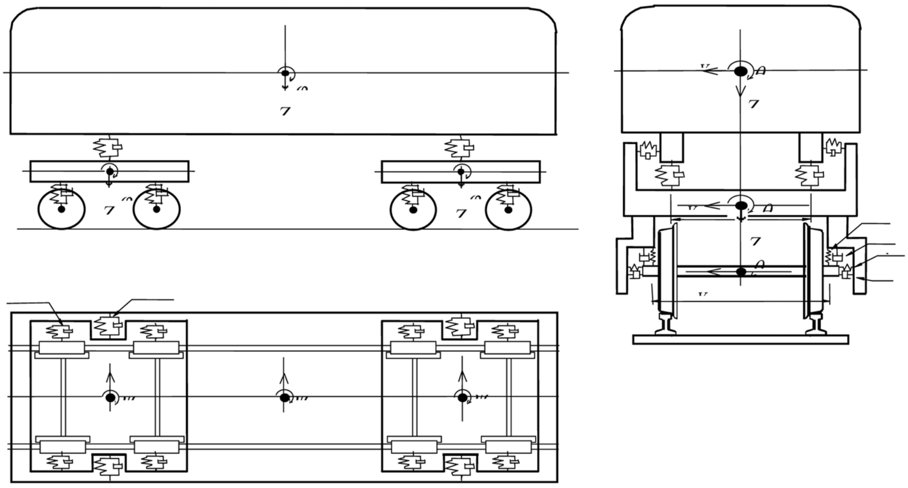


Fig. 3 Vehicle computational model

To simplify the analysis, the following assumptions are made for the vehicle model:

(1) The car-body, bogies and wheel-sets are regarded as rigid elements connected to each other by linear springs and viscous dashpots. The car body is symmetrical about its mass center in left and right as well as front and rear;

(2) The train makes uniform motion along longitudinal axis of the bridge, disregarding the effect of longitudinal dynamic forces, and wheel and rail keep in contact to each other.

2.3 Numerical solution of the dynamic system

The spatial model for train-station dynamic interaction consists of the train model and the station model that are combined to each other according to relationship between rail and wheel movements. Based on the dynamics theories, the dynamic equations for station and vehicle, which are bordered with each other by the rail-wheel contact surface, are established respectively. The step-by-step integral method is adopted to analyze the train-station coupling vibration. Under the prerequisite that the wheelset does not jump off the rail, its motion equation is established based on the wheel-rail geometry theories and the creep theory of wheel-rail contact. The elastic effects of the track system are neglected. The convergence condition is that relative error, produced after two iterative results of acting force between wheelsets and rail, is less than the allowable error. This method can be used to solve non-linear dynamic problem and the dynamic response problem generated when a train moves on and leaves the station car by car.

2.4 Calculation condition

The Chinese electric motor train unit, with 6 motor cars and 2 trailers in composition is used in the analysis, and the calculation train speeds are 200, 250, 280, 300, 320 and 350 km/h.

The German low-interference track spectra is used to conduct simulation calculation. The generated irregularity sample has wavelengths from 1 m to 80 m, with the level, alignment and cross-level irregularity altitudes being 7.59 mm, 5.5 mm and 3.95 mm, respectively.

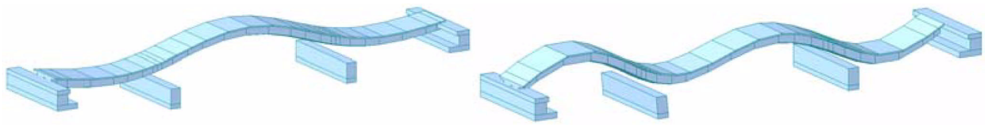


Fig. 4 First and second vertical mode shapes of 30.9 + 49 + 30.9 m continuous beam

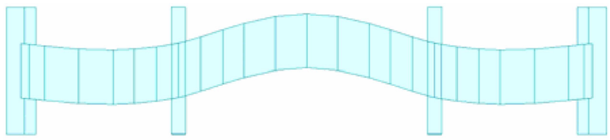


Fig. 5 First lateral mode shape of 30.9 + 49 + 30.9 m continuous beam

3. Natural frequences and mode

3.1 Main line bridge

The first natural frequencies of the 30.9 + 49 + 30.9 m continuous beam in the vertical and lateral direction are 3.224 Hz and 7.245 Hz, respectively, and the second vertical natural frequency is 6.262 Hz. The corresponding mode shapes are shown in Figs. 4 and 5. The measured top 2 vertical frequencies are 3.58 Hz and 6.91 Hz. The calculation and test results are basically consistent.

3.1.1 Whole station

The top 20 mode shapes of the station are local vibration at roof and waiting hall floor. The typical mode shapes are shown in Figs. 6 and 7.

4. Train-station dynamic analysis result

4.1 Calculation phases

The first stage of calculation is accomplished on the basis of design drawings, but it is found that theory values are generally smaller than those from field tests. The results of analysis and measurement are very close in the adjacent district of the main-line bridge, but with the increase of distance from the main line, the calculation results decreased quickly while the test values decayed much slowly. The differences can be caused by the following 3 reasons:

(1) According to design drawings, the main line bridge that supports high-speed track is completely separated from other parts, and the vibration can only be transferred through piers. In fact, the distance between the main-line bridge and its nearby arrival-departure track bridge is very small. The vibration of continuous beam can be directly spread out through accessory structures such as cover slabs;

(2) The roof and waiting hall are composed by steel truss, but platform layer is supported by concrete beams. The equivalent damping ratio should be a number between 0.01 and 0.02. If 0.02 is adopted, the smaller results can be expected;

Fig. 6 The first mode shape of station (local vibration of roof, $f = 1.009$ Hz)

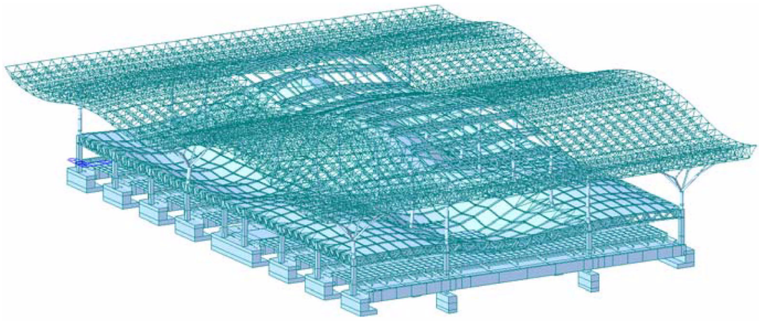


Fig. 7 The 12th mode shape of station (local vibration of waiting hall floor, $f = 2.021$ Hz)

(3) In theoretical analysis, the weight and its distribution of the station structure are considered according to the design, and all accessory equipments are included. But actually some of its weight has not occurred within the experiment, and this will also lead to smaller calculation results.

Therefore, the dynamic analysis model is modified. The Master/slave constraints between main-line bridge and arrival-departure track bridge are disposed, and damping ratio is changed into 0.01.

Then the second phase of calculation is carried out. The layout of station measuring points is shown in Fig. 8.

4.2 Influence of distance on the acceleration at waiting hall floor

The theoretical analysis indicates that the acceleration decrease with the increase of distance from the main line. The acceleration histories of 1#, 3# and 5# points are shown in Fig. 9.

4.3 Comparison of numerical results from the first and second phases

The two phase calculation consequences are shown in Table 1. In the calculation, the train speed is 350 km/h.

It can be seen that the dynamic responses in the second phase are obviously greater than those in the first phase in all points of the two spans, and the differences become more visible as the distance from the line increases. Compared with the field tests, although the analysis results are still slightly smaller, a significant improvement has been obtained.

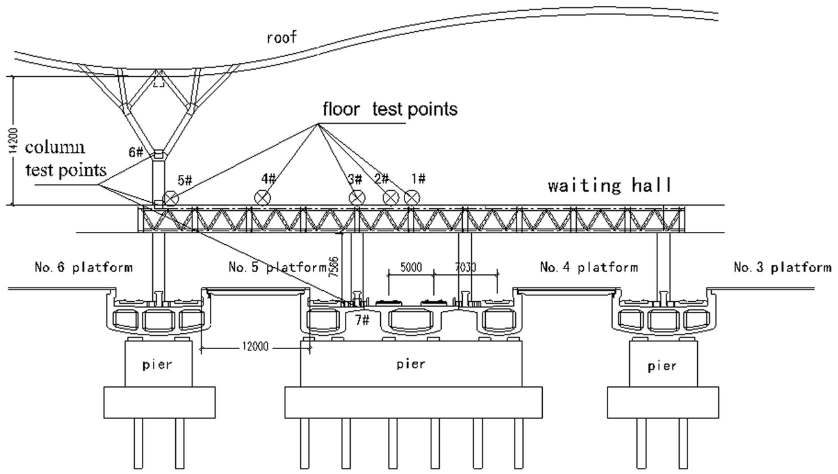
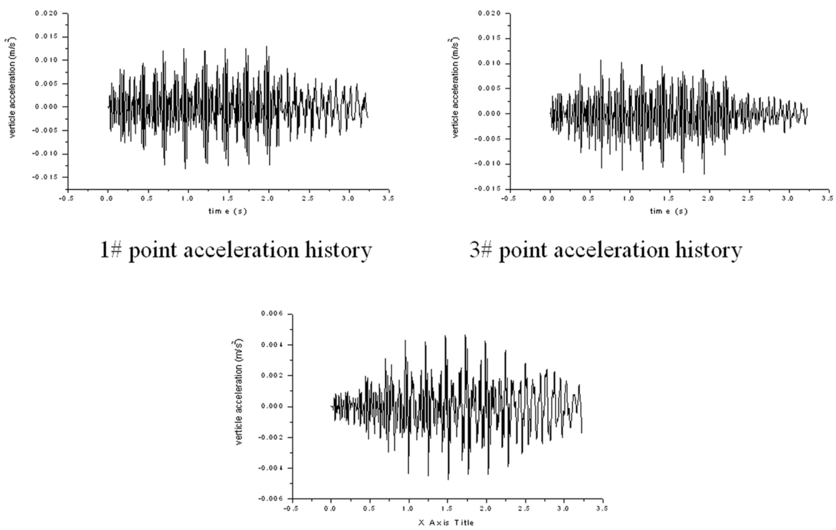


Fig. 8 The layout of station measuring points (1#~7# stand for output points)



1# point acceleration history

3# point acceleration history

5# point acceleration history

Fig. 9 Acceleration histories of theoretical analysis

Table 1 Comparison of calculated accelerations from first and second phases (m/s^2)

location	1# point		3# point		4# point		5# point	
	first phase	second phase	first phase	second phase	first phase	second phase	first phase	second phase
Mid-span of 30.9 m	0.0052	0.0132	0.0067	0.012	0.0074	0.0094	0.0001	0.0051
Mid-span of 49.0 m	0.0071	0.0125	0.0037	0.0226	0.0099	0.0133	0.0015	0.013

5. Conclusions

The following conclusions can be drawn from this study:

(1) Due to the distance between main-line bridge and its nearby arrival-departure track bridge is very small, the vibration can be directly spread out through accessory structures such as cover slabs. This phenomenon should be taken into account in similar analysis.

(2) The roof and the waiting hall are composed by steel truss, but the platform layer is supported by concrete beams. If the vibration of waiting hall is more concerned, the equivalent damping ratio should be between 0.01 and 0.02.

References

Adams, G.G. and Bogy, D.B. (1974), "Steady solutions for moving loads on elastic beams with one-sided constrains", *J. Appl. Mech. - T. ASME*, **42**, 800-804.

Chu, K.H. and Garg, V.K. (1979), "Railway-bridge impact:simplified train and bridge model", *J. Struct. Division - ASCE*, **105**(9), 1823-1844.

Fryba, L. (1987), "Dynamic interaction of vehicles with tracks and roads", *Vehicle Syst. Dyn.*, **16**, 129-138.

Gao, M.M. (2001), *Studies on train-track-bridge coupling vibratiion and runnablility of train on high-speed railway bridges,* Doctor Thesis, China Academy of Railway Sciences.

Gao, M.M. and Pan, J.Y. (2005), "Coupling vibration analysis for train-track-bridge system", *Proceedings of EURODYN 2005*, Paris, 1069-1075.

Kalker, J.J. (1979), "Survey of wheel-rail rolling contact theory", *Vehicle Syst. Dyn.*, **8**(4), 317-358.

Ministry-Issued Standard of PR China (2004), Code for Rating Existing Railway Bridge Bridges, Railway Press, Beijing, China.

Ministry-Issued Standard of PR China (2004), Temporary Provisional Regulations on Design of Newly Built Railway Lines for Passenger Traffic of 300-350km/h. Railway Press, Beijing, China.

Shinozuka, M. and Jan, C.M. (1972), "Digital simulation of random processes and its applications", *J. Sound Vib.*, **25**(1), 111-128.

State Standard of PR China (1985), *Railway vehicle-specification for evaluation the dynamic performance and accreditation test*, GB 5599-85, Railway Press, Beijing, China.

Tanabe, M. and Wakui, Y.Y.H. (1987), "Modal method for interaction of train and bridge", *Comput. Struct.*, **27**(1), 119-127.

Wang, F. T. (1994), *Vehicle dynamics*, Beijing, China Railway Press.

Xia, H. and Zhang, N. (2005), *Dynamic interaction of vehicle and structures (2nd Edition)*, Beijing, Science Press.

Yang, Y.B. (2008), "Wind-induced aerostatic instability of cable-supported bridges by a two-stage geometric nonlinear analysis", *Interact. Multiscale Mech.*, **1**(3), 381-396.

Yau, J.D. (2009), "Vehicle/bridge interactions of a rail suspension bridge considering support movements", *Interact. Multiscale Mech.*, **2**(3), 263-276.

Zhai, W.M. (2007), *Vehicle-track coupling dynamics (3rd Edition)*, Beijing, Science Press.

Zhai, W.M., Cai, C.B. and Guo, S.Z. (1996), "Coupling model of vertical and lateral vehicle/track interactions", *Vehicle Syst. Dyn.*, ***26***(1), 61-79.

Zhang, N., Xia, H. and De Roeck, G. (2007), "Spectrum and sensitivity analysis of vehicle-bridge interaction system", *Proceedings of. ISEV2007*, Taipei, 357-362.