Research on Threshold Value of Seismic Urgent Handling System of High-speed Railway Train

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SUMMARY:
In order to reasonably obtain the threshold value of Earthquake Urgent Automatic Alarm System (EUAAS) of running trains with different speeds, the coupling dynamic model of train-bridge system is established, the track irregularities are simulated by trigonometric series method and several typical seismic records are selected. A calculation program is developed to solve the train-bridge coupling vibration equations. The earthquake dynamic responses of train-bridge system are analyzed under track irregularity and typical earthquake excitations. By comparative analysis with the standards, several reaction indexes are used to evaluate the safety of the train. The effect of the train speed and seismic dynamic strength to the safety of running trains is summarized, and preliminary suggested threshold values of seismic urgent handling system under different running speeds are presented.

Keywords: earthquake emergency handling, high-speed railway, vehicle-bridge coupling, alarm threshold

1 INTRODUCTION

The speed of high-speed train has been increased a lot than normal train, when the train speed exceeds 200km/h, even an earthquake with a small magnitude may lead to serious consequences that may make the train out of working, derailment, cause damage to the railway bridge, or even threaten people's life[1].Therefore, to improve the ability of decreasing disaster and ensure the safety of passengers' lives and property, it is of important and practical significance to research the seismic urgent handling system of high-speed railway.

At present, there are already several seismic alarm systems which sent out alarm signals according to seismic peak acceleration, but few methods on determination of peak value are published[2]. China's limit value of lateral acceleration of track is preliminary suggested as 120Gal refer to foreign standards and earlier research achievement of Beijing-Shanghai high-speed railway[3], hereby, the alarm threshold of mechanical-driven seismometer can be derived by the formula: EAT=[A]/D=120/2.55=47(Gal), A represents the limit value of lateral acceleration of track, D represents the maximum value of dynamic-response factor under different earthquake excitation，the value of D is 2.55 when the guarantee probability come up to 95%. For the sake of safety, the alarm threshold value is suggested as 45 Gal[4]. However, this alarm threshold value has certain risk and do not take the vehicle speed into consideration. Actually, when the speed is low the train emphasis on safety, alarm threshold can be increased appropriately to avoid unnecessary emergency brake in a relatively safe situation. At the same time, Alarm threshold should be accordingly reduced when the speed is high. Therefore, in this paper further study on the alarm threshold values of running train on high-speed railways are carried out, based on the research of ground motion parameters of running trains at safety condition.

For the development status of high-speed railway in China, considering influence factors of terrain condition, deformation, subsidence, ride comfort of train and economy, the railway bridge has irreplaceable superiority compared with subgrade. In the built passenger dedicated railway, the proportion of the cumulative length of railway bridge to the total length of railway has reached to almost 80% (showed in Table 1)[5], thus, the study on alarm threshold value of the running train in this paper are mainly focused on the railway bridge.

Table 1 Proportion of the cumulative length of railway bridges to the total length of railway

Jing-Jin Passenger-Dedicated Railway	Beijing-Shanghai High Speed Railway	Guangzhou-Zhuhai Intercity Railway	Shi-Tai Passenger Dedicated Railway
95.9%	80.5%	94.0%	82.0%

2 METHOD OF SEISMIC RESPONSE ANALYSIS FOR TRAIN-TRACK-BRIDGE SYSTEM

The high-speed train-track-bridge coupling dynamic model is composed of the rolling stock, track, and bridge which are coupled as a whole system by dynamic coupling relationship between wheel and rail and interaction between track and bridge during an earthquake. Seismic loads are treated as external excitations which act on bearing points of bridges. The rolling stock can be regarded as multi-rigid-body system which is connected by springs and dampers, the bridge is respectively simulated by bar element, beam element and plate element, coupling vibration between vehicle and bridge is connected by the relation of wheels and rails. Fig.1 shows the coupling dynamical model of train-track-bridge.

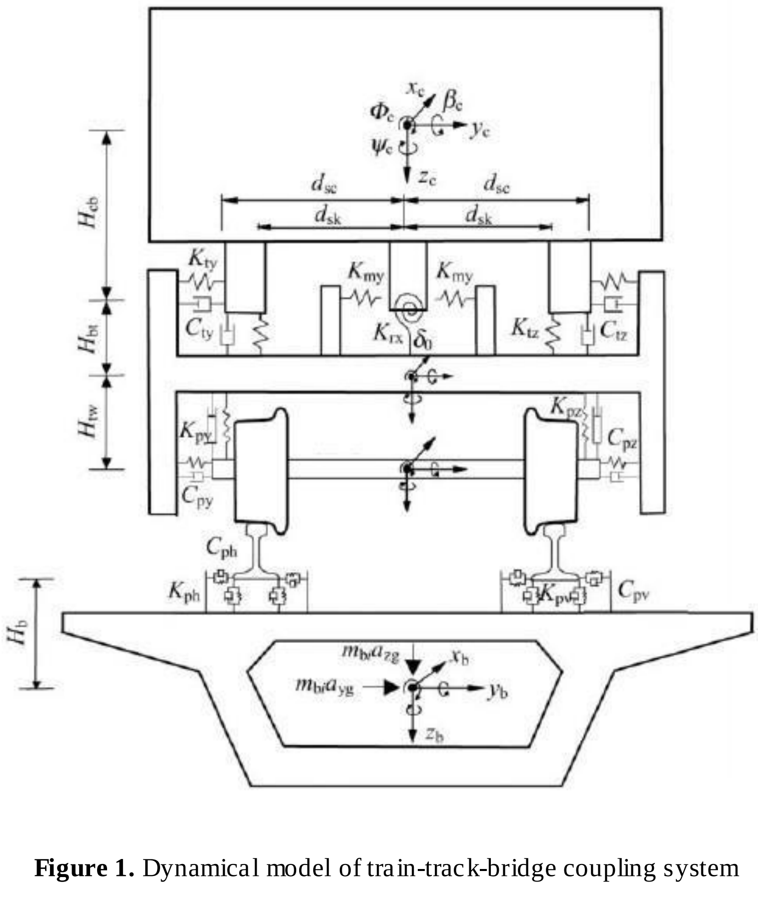

Figure 1. Dynamical model of train-track-bridge coupling system

2.1. Vehicle Model

Each vehicle includes a single body, two bogies, four wheel Sets and suspension system of springs and dampers of these three parts. In order to simplify the analysis process and ensure the accuracy, assumptions are made as follows[6]:

(a) Car body, bogies and wheel sets of each vehicle are all treated as rigid bodies, elastic deformations are ignored during the vibration.
(b) Springs and damps connecting the rigid body are linear.
(c) Longitudinal vibrations of vehicle body, bogies and wheel sets are not considered.
(d) Five degrees of freedom include lateral movement, bouncing, nodding, yaw and roll are considered for the car body and two bogies, while for wheel sets, only four degrees of freedom are selected which include lateral movement, bouncing, yaw and roll.

For the four-axle vehicle with two bogies, each one totally has 31 degrees of freedom.

Vehicle dynamics model and vibration equations are established according to the selected vehicle model. For the 31 degrees of freedom, the dynamic equations of each degree of freedom are built separately based on d'Alembert principle, and the equilibrium equation of vehicle dynamic can be written in matrix form:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{P\}+\{Q\} \quad (2.1)$$

Where, $\{U\},\{\dot{U}\},\{\ddot{U}\}$ are the displacement, velocity, acceleration vector of the train; [M],[C],[K] are mass, damping, stiffness matrix of the train;{P} is the external load acting on the train, which is mainly refer to the wheel-rail force; $\{Q\}=-[M]\{a_g(t)\}$ is seismic inertia force, $\{a_g(t)\}$ is the vector of ground motion acceleration.

2.2 Bridge model

Railway bridges are composed of bridge piers, beams, floor systems, bridge tracks and etc. Vehicle loads are transmitted to the bridge through wheel and rail. In the research, it proposes with the hypotheses that there is no relative displacement between tracks and bridge decks, and the elastic deformations between bearing plate bars and fasteners are ignored. For vehicle-bridge coupling dynamic equation, motion equations of vehicle are not directly combined with finite element model of bridges, but combined with generalized coordinates of bridge vibration mode. Bridge is dispersed into many beam elements in the vehicle-bridge coupling system, then, a suitable interpolation function is selected, to calculate the kinetic energy and strain energy of each element. Motion equations of structure are derived by direct integration method or mode superposition method.

According to the above assumptions and analysis, section displacements of the pre-stressed box beam can be decomposed into transverse displacement Y_b, vertical displacement Z_b and torsional displacement θ_b of shear centre. The bridge structure can be discretized into 3-Dimentional finite elements model, the corresponding motion equations of bridge joints can be obtained as follows:

$$[M_b]\{\ddot{X}\}+[C_b]\{\dot{X}\}+[K_b]\{X\}=\{F\} \quad (2.2)$$

Where, $\{\ddot{X}\}$, $\{\dot{X}\}$, $\{X\}$ are the displacement, velocity, acceleration vector of the bridge joints, $[M_b]$, $[C_b]$, $[K_b]$ are mass, damping, stiffness matrix of the bridge, {F} are the force vectors acting on the bridge joints, which can be obtained by the formula: $F=F_e+F_w$, F_e represent the external forces acting on the bridge joints, F_w represent wheel sets forces from the train transmitted by the track.

2.3 Simulation of track irregularity

At present, China has no track spectrum standard of trains under high-speed running condition, during the research of general technical specifications of high-speed train, foreign track spectrums of high-speed railway are selected for dynamic emulation analysis on bridge-vehicle system of high-speed railway. Track irregularity PSD of Germany's high-speed railway is widely adopted by European railway system and it is also the suggested spectral density function in China's general technical specifications to analyse running stability of high-speed train[7]. Because the train speed exceeds 250km/h in the study, the Low interference spectrum of Germany's high-speed railway is selected for the research and superposition method of trigonometric series is used during the numerical simulation.

2.4 Selection of seismic waves

In order to obtain the alarm threshold, two seismic wave components of horizontal direction and vertical direction are considered, three seismic records from the station of ALS, CHY008 and CHY004 in the Taiwan Chi-Chi earthquake are selected, and the three records respectively correspond to the hard soil, medium soil and soft soil. Besides, to make solutions more accurately, three typical seismic records including El Centro, Taft and Kobe waves are also selected. The six selected seismic wave data are standardized before calculation.

2.5 Solution to the dynamic equilibrium equation of vehicle bridge system

Combining and arranging the above simultaneous motion equation of vehicle bridge system, a formula of motion equation for vehicle-bridge interaction system can be set up as follows:

$$\begin{bmatrix} M_{vv} & 0 \\ 0 & M_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{x}_v \\ \ddot{x}_b \end{Bmatrix} + \begin{bmatrix} C_{vv} & C_{vb} \\ C_{bv} & C_{bb} \end{bmatrix} \begin{Bmatrix} \dot{x}_v \\ \dot{x}_b \end{Bmatrix} + \begin{bmatrix} K_{vv} & K_{vb} \\ K_{bv} & K_{bb} \end{bmatrix} \begin{Bmatrix} x_v \\ x_b \end{Bmatrix} = \begin{bmatrix} F_v + F_v^* \\ F_b + F_b^* \end{bmatrix} \tag{2.3}$$

Where F_v and F_b are the force vector of vehicle and bridge without considering earthquake effect; F_v*、F_b* are the seismic force velocity of vehicle and bridge; $\ddot{x}_v$、$\dot{x}_v$、x_v are respectively represent the motion acceleration, vector and displacement of vehicle; $\ddot{x}_b$、$\dot{x}_b$、x_b re respectively represent the vibration acceleration, vector and displacement of bridge; M_{vv}、M_{bb} are the mass matrix of vehicle and bridge; C_{vv}、C_{bb} are the damping matrix of vehicle and bridge; K_{vv}、K_{bb} are the stiffness matrix of vehicle and bridge; C_{vb}、C_{bv}、K_{bv}、K_{vb} are respectively represent the damping matrix and stiffness matrix of vehicle-bridge interaction.

Based on the platform of Matlab software, a calculation program is established, and the motion equation as well as the dynamic response of vehicle-bridge system is finally analyzed and solved. Because the coupling system is a nonlinear time-varying system, Newmark-β method is adopted during numerical calculation which is described detailed in literature[8].When considering track irregularity, to time step t, take the state value of bridge at the former time step as the initial iterative value, combining the track irregularity value at time t, equivalent track irregularity value can be obtained[9];Wheel rail dynamic coupling model is adopted in the calculation program[10]; To get the wheel rail contact geometry relation and calculate wheel-rail force, elastic contact deformation and transient detachment between the wheel and rail can be considered so that dynamic characteristics of wheel-track interaction can be described more accurately.

3 EVALUATION STANDARDS FOR THE SAFETY OF HIGH-SPEED TRAIN

The basic requirement of the running train is safe and then stable. During the dynamic performance evaluation of rolling stock, certain indexes such as derailment coefficient and wheel unloading rate are often used to evaluate the operation safety of high-speed train. The most direct index to evaluate vehicle smoothness is vibration acceleration of vehicle-body including horizontal acceleration and vertical acceleration. The dynamic performances of vehicle and track are evaluated by comprehensive consideration of wheel-rail dynamic force and dynamic deformation of track structure.

The indexes including derailment coefficient, horizontal acceleration of vehicle-body and lateral force between wheel and rail are selected for the analysis and judgment of vehicle-bridge system. The limit value of derailment coefficient for the train on bridge is taken as 0.8 and the limit value of lateral force between wheel and rail is taken as 80KN based on the Interim Design Provisions for a New 200 km/h

Mixed Passenger and Freight Railway of China, horizontal acceleration of vehicle-body is taken as 0.10g according to Dynamic Irregularity Management Standard for 200-350km/h Track Inspection Car of China.

4 PARAMETER STUDY ON ALARM THRESHOLD VALUE

4.1 Selection of calculation parameters

The common spatial model of high-speed train is chosen, as the calculation model, it proposes with the hypotheses that there are six vehicles on the bridge, the parameter values of which are put forward by Wang Boming in his research work[11]. The bridge model is considered as a double-track bridge composed of nine-span simply supported beams with the span of 32m, pier height of 10m[12]. The beam section of bridge is shown in Fig. 2 and the basal calculation parameter values of bridge are shown in Table 2.

Table 2 Main calculation parameters of bridge

Area(m^2)	I_{xx}(m^4)	I_{yy}(m^4)	I_{zz}(m^4)	Density(kg/m^3)	Elastic modulus (Gpa)	Poisson ratio
8.944	23.497	11.201	84.967	2500	34.5	0.2

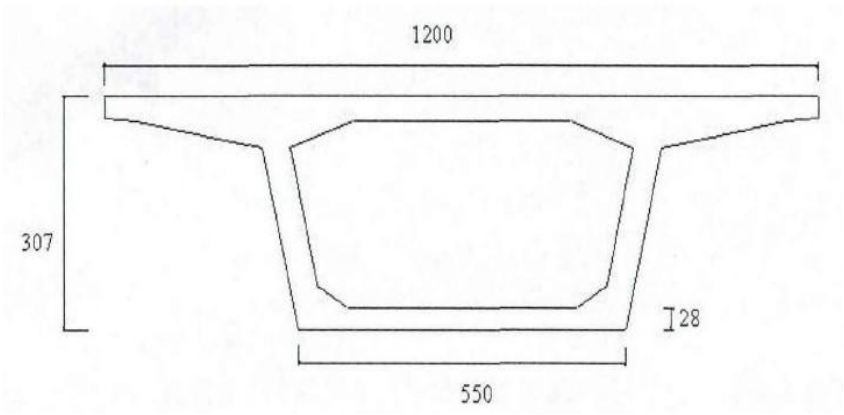

Figure 2. Beam section of the bridge

4.2 Calculation cases and result analysis

The limit value of lateral acceleration of tracks is determined by dynamic response analysis on vehicle-bridge coupling model. By comparative analysis with the standards, several reaction indexes are used to evaluate the safety of the train, the critical value which endanger the train is the limit value of lateral acceleration of tracks.

During the seismic response analysis of the model, horizontal peak ground acceleration of seismic waves are adjusted from 0 to 0.24g with a step of 0.02g and the speed adjust from 0 to 400km/h with a step of 20km/h, then the secure indexes are calculated, the variation curves of the derailment coefficient, vehicle-body horizontal acceleration and lateral wheel-rail force with the change of earthquake intensity are obtained.

By integrating the calculation results of the six seismic waves, the safety indexes are plot and the maximum values are chosen for further analysis. Finally, the limit value curves of earthquake intensity at different speeds are obtained. Fig. 3, 4 and 5 respectively shows the limit values of earthquake intensity determined by safety standards of derailment coefficient, vehicle-body horizontal acceleration and lateral wheel-rail force.

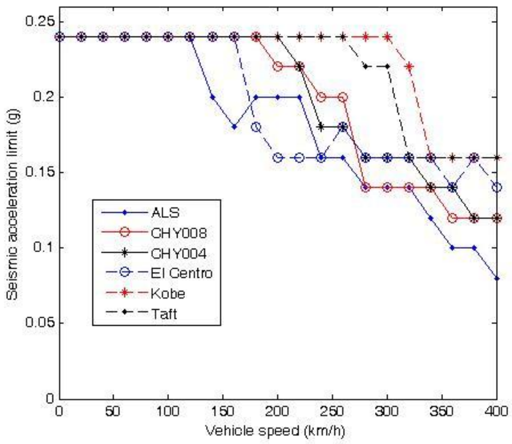

Figure 3. Limit values of seismic intensity determined by derailment coefficient

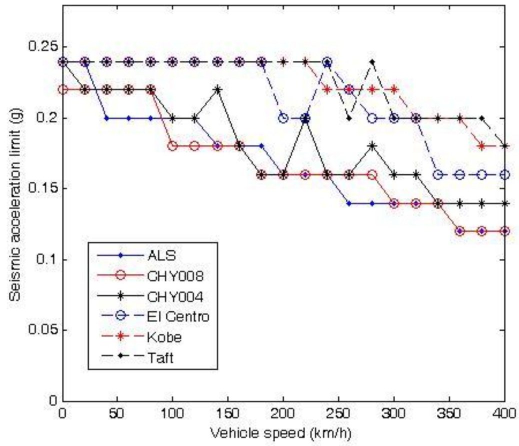

Figure 4. Limit values of seismic intensity determined by vehicle-body horizontal acceleration

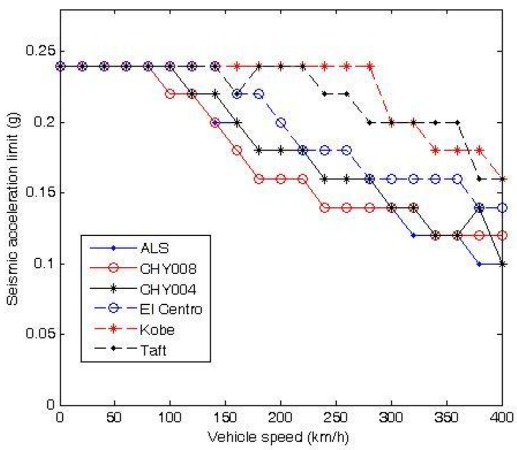

Figure 5. Limit values of seismic intensity determined by lateral wheel-rail force

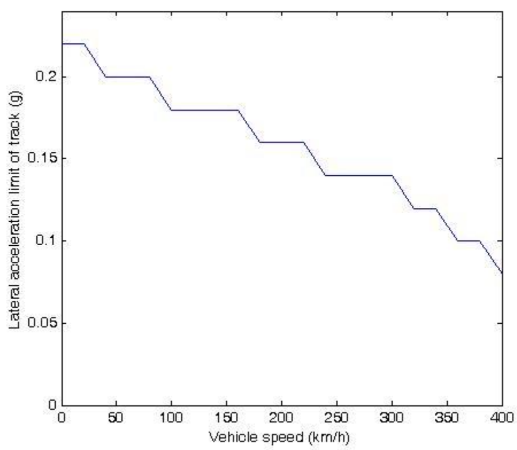

Figure 6. Limit values of lateral acceleration of tracks at different speed

According to the safety index, limit value curves of earthquake intensity showed in Fig. 3, 4 and 5 are integrated. Taking the minimum value, the limit value curves of lateral acceleration of tracks under different speeds can be obtained. The result is shown in Fig. 6.

During the calculation, it can be found that, owing to different spectral characteristics of seismic waves, when the seismic data is different, the results of safety index values are various. In addition, it is obviously that the results will vary when vehicle parameters, such as track irregularity samples, calculation models, differ even with the same train speed and earthquake. Therefore, the results showed in Fig. 6 do not represent the general situation, certain security extra should be considered when formulating the alarm thresholds, and in order to ensure the safety of the running train and make the function form more concise, the results of EAT should be reduced and simplified, values of EAT (Gal) are presented can in Eqn. 4.1 and shown in Fig. 7.

$$\mathrm{EAT(V)} = \begin{cases} 60 & \mathrm{V} \le 200 \\ 92 - 0.16\mathrm{V} & 200 < \mathrm{V} \le 400 \end{cases} \tag{4.1}$$

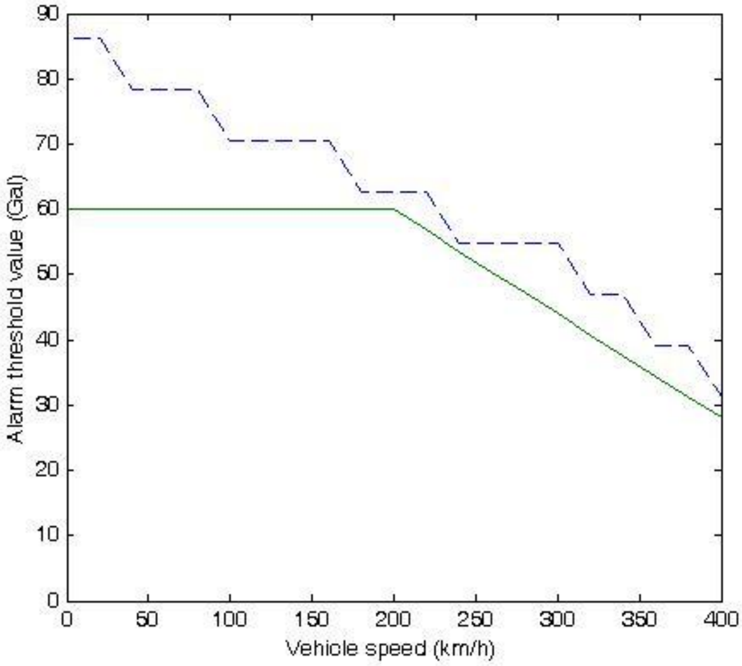

Figure 7. Values of EAT at different speeds

In China, a train can be regulated as high speed train when its speed exceeds 200km/h, otherwise, when the train speed is lower than 200km/h, the value of EAT can be set to 60 Gal, because small earthquake cannot cause a serious impact on the running train. When the vehicle speed exceeds 200km/h, the effects of earthquake on safety of running trains are increasing, thus the alarm threshold values should be lower as the speed increases. The value of EAT can be set to 36 Gal when the vehicle speed is 350km/h.

5 SUMMARY AND SUGGESTIONS

The train-track-bridge coupling dynamical model is established in this paper, and by analysing dynamic responses of vehicle-bridge system under seismic excitations, lateral acceleration limit values of tracks are obtained by comparative analysis with the secure index. Thus a preliminary suggestion of the seismic emergency handling threshold values under different vehicle speeds of high-speed railway system is put forward.

(a) The running train will become more dangerous with the increase of the vehicle speed and earthquake intensity. The limit value of earthquake intensity for safe operation of the train will decrease when the vehicle speed increases.
(b) The value of EAT can be set to 60 Gal when the vehicle speed is below 200km/h, when the vehicle speed exceeds 200km/h, the threshold value has a linear decrease as the increase of train speed. When the vehicle speed is 350km/h the value of EAT can be set 36 Gal.

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