Analysis of Bridge Dynamics and Response Characteristics Under The Influence of Axle Coupling Vibration

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Abstract

To ensure the safety and stability of high-speed rail lines and reduce external interference, it is essential to build a large number of elevated bridges. These elevated bridges account for a considerable proportion of the total length of high-speed rail lines. However, when high-speed rail lines pass through earthquake prone areas, the likelihood of earthquakes occurring when trains pass through bridges increases significantly. Therefore, it is necessary to study the dynamic response of bridge structures under earthquake action to ensure the safety of bridges during train operation and operation. The optimization scheme proposed in this article has undergone moderate impact tests, and the results show that the maximum lateral displacement of the bridge can reach 124 mm, while the maximum vertical acceleration is 5.16 m/s^2, Exceeded the safety limit of 0.35 g. Through the analysis of train derailment coefficient, wheel load reduction rate, lateral sway force, lateral and vertical acceleration, and Spelling comfort index, we have come to the conclusion that bridges can

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ensure the safety of train operation in the absence of earthquakes and small earthquakes, and can also maintain certain stability under medium and large earthquakes. These research results have important guiding significance for the design and construction of high-speed rail lines. By optimizing the bridge structure and adopting relevant technical measures, the seismic disaster resistance of high-speed rail lines can be further improved, ensuring the safety and comfort of passengers during travel. At the same time, these research results also provide useful reference and inspiration for the construction and improvement of future high-speed rail lines.

Keywords: Earthquake, continuous steel truss girder bridge, high-speed train, time-variable system, coupling vibration.

1 Introduction

The research work of axle vibration has a history of more than one hundred years from the emergence of railway traffic to the construction of modern high-speed railway. Among them, before the 1960s, the classical axle research stage, the main research method is mainly test, theoretically obtained the analytical or approximate solution of several simplified models; after the 1960s, the computer is widely used to solve the train elasticity, which is the research stage of modern axle vibration [1, 2]. In 1849, Willis submitted the first study report on bridge vibration (exploring the cause of Chester railway bridge collapse). He simplified the vehicle to the mobile concentration force, ignored the mass of the bridge, established the vibration equation of the simple supported beam bridge [3, 4]. The analytical solution for this particular problem was derived, and the series method was employed to obtain an approximate solution. Between the years 1905 and 1908, Krylov and Timoshenko elucidated the differential equation pertaining to the bridge and subsequently derived the analytical solution concerning the vertical vibration response of the said bridge. From 1934 to 1937, SchallenkampAl took into account the quality of vehicles and bridge, simplified the train load into the periodic force and force of inertia, analyzed the problems of single wheel bridge, and made a preliminary analysis of the mass problems of the spring, the action of the moving wheel and the uneven track [5, 6].

The prototype test organized by the United States in 1907–1910 concludes that the unbalanced hammer force of steam locomotive is the main cause of bridge vibration, and first gives the concept of impact coefficient and the first power impact coefficient curve. In the second test from 1919–1921, the concept of "critical speed" is obtained, which occurs when the wheel speed approaches the bridge base frequency. The third test conducted in the United States in 1941 showed that the bridge was impacted the most when the train speed was 33–50 km/h [7, 8], compared the difference between bridge vibration caused by steam locomotive and diesel locomotive, and pointed out that the maximum impact coefficient of diesel locomotive was 70% −75% of steam locomotive. The former Soviet Union in 1927 to 1936 to cause the bridge vibration of various factors a lot of experimental research, its prominent characteristic is to consider the transverse vibration of the bridge [9, 10], and on the basis of the test of transverse vibration "curtain" theory, "lateral swing" theory, gives the transverse vibration stress coefficient with the speed of the empirical formula. In view of the great difference between the train type and running speed and the working conditions of modern railway bridge, the conclusion is of little significance to the current bridge design theory, but some basic concepts proposed at this stage, such as impact coefficient and bridge resonance, have been used today.

In 1953, scholars from the former Soviet Union successively used the integral equation method and the Calekin method to make a strict analysis of the problem of considering both the quality of the bridge itself and the quality of the live load [11, 12]. These simplified models are still widely used in frontier topics such as bridge dynamic analysis and bridge moving load identification. In 1905, Claussek regarded the unbalanced hammer force of the moving wheel of the locomotive as a single periodic force moving along the bridge span. ignoring the quality of the locomotive, the locomotive spring and the irregularities of the track, the vertical vibration solution of the continuous beam bridge was obtained according to the inherent vibration type expansion method. He also fixed the inertia force of the locomotive in the appropriate position of the bridge to consider the inertia force of the locomotive.

2 Vibration Analysis Model of the Time-variable System of Train-steel Truss Bridge

2.1 Finite Element Bridge Model of Three Truss Sections

Train-steel truss girder bridge system is a more complex time-varying system, the dynamic analysis should adopt the idea of energy theory, by the elastic system dynamics total potential energy constant value principle and formation matrix "accordingly" law can guide the car a bridge system stiffness matrix, mass matrix, damping matrix and load array, and then solve [13, 14].

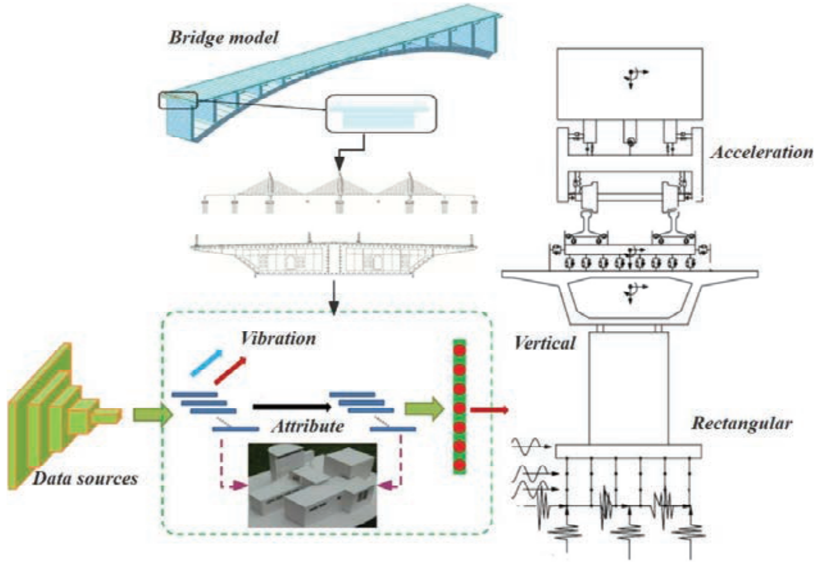

Figure 1 Bridge diagram.

There are three main analysis methods for truss beam: analysis by space rod unit or beam unit. In theory, the accuracy of this calculation method is more guaranteed, but this method causes a lot of freedom, a large calculation amount and a long calculation time, which is very uneconomical for the vibration analysis of the axle. Analysis of converting truss beams into thin-wall closed-section box beams. However, this method does not consider the joint action of the main truss and the upper and lower vertical inclined bar and chord, it is difficult to consider the role of the inclined bridge gantry, and the cross connection is similar, which can only be used for the analysis of parallel string truss, but not for non-parallel string truss. Truss-section finite element method. Is a section of the truss (usually a node) as a unit of the finite element, the connection between the units at four angles. This method basically assumes less and calculation work, high calculation accuracy, can be used for parallel string and non-parallel string truss beam analysis, which is very effective for considering local components. Figure 1 This method is used to establish the bridge finite element model [15, 16].

The mathematical model of this article takes into account the influence of bridge deck deformation, using finite elements of two main trusses [17, 18], and Equation (1) uses finite elements of three main trusses. The spatial beam elements of the bridge piers are discrete, while the planar rectangular elements of the bridge deck are discrete.

$$\alpha(z,t) = \alpha_i(t)(s-z) + +\alpha_j(t)z/s \tag{1}$$

The truss unit used in this paper has the following characteristics: assuming that except for the bridge door frame and transverse connection [19, 20], All the rods of the truss beam are hinged to each other; Ignoring the influence of railway bridge deck system and track stiffness; Ignore the axial deformation of the upper and lower vertical bar bars of the truss beam; The mass of each internode of the truss beam is concentrated in the junction cross-section, The mass condensation method is: the chord mass is condensed at 6 corner points; The mass of the upper and lower vertical connection is condensed in the upper and lower angles close to it respectively; The mass of the vertical rod and the belly rod condenses in the midpoint of the main truss; The mass of the bridge deck and the track and the sleepers condenses at the intersection of the vertical and horizontal beams, And also assume a linear distribution of the points on the beam, Deided by the underchord displacement of the main truss; The displacement at the middle point of the main truss is the average displacement of the upper and lower corners. Since the rods of the truss are hinged with each other and the displacement is only continuous between the units, the linear displacement function is shown in Equations (2), (3) and (4), where S is the length of the unit and Z is the local coordinate of the unit.

$$V_m = \chi_1(\chi_2\delta_3 + \beta_2 B_4) + \beta_1(\chi_1 B_5 + \beta_2 B_6) \tag{2}$$

$$W_m = \chi_1(\chi_2 B_9 + \beta_2 B_{10}) + \beta_1(\alpha_2 B_{11} + \beta_2 B_{12}) \tag{3}$$

$$D_m = U_m S_1 + V_m S_2 + W_m S_3 \tag{4}$$

For the large-span continuous steel truss bridge, if each node is taken as a truss section unit, the number of freedoms of the whole bridge is very large [21, 22], which not only brings some difficulties to the solution, but in fact is completely unnecessary. In the linear displacement mode shown in Equation (5), some simplified measures can be taken by taking multiple internodes as a truss unit. However, in order to ensure a certain accuracy, not each truss unit takes so many nodes as a unit, such as near the support or take a node as a unit. Because the force near the support is concentrated, the seat significantly improves the accuracy of the problem.

$$V_{ms} = X_{s1} M_s H_s + X_{s2} M_s H_{s2} + X_{s3} M_s H_{s3} + Y_{s1} M_s H_{s1} \tag{5}$$

For the truss unit i, j, establish the local coordinate system shown in Equation (6). If you want to calculate the tensile and compression strain energy of a certain rod in the truss section, the Equation (7) only needs to know the lateral, vertical. The direction cosine is not difficult to find, so now the problem is transformed into a point in the truss section, the linear cell displacement mode shown in Equation (8) when the m point is on the left of the truss section:

$$X_m = X_c - h_i\delta_c + L\delta_c - X_{gq} - h_2\delta_{gq} \tag{6}$$

$$Y_m = X_c - h_l\delta_c - L\delta_c - X_{gh} - h_2\delta_{gh} \tag{7}$$

$$Z_m = \frac{1}{2}(V_{r1} + V_{l1}) + \frac{e}{B}(V_{r1} - V_{l1}) + y_{v1} \tag{8}$$

2.2 Vehicle Space Vibration Analysis Model

The spatial vibration analysis model of vehicle (locomotive) is shown in Equation (9), using the following assumptions: car body, bogie and wheel pair are rigid [23, 24]; excluding the longitudinal vibration of locomotive and vehicle and its influence. The wheel pair, bogie, and car body exhibit micro vibrations. All springs are characterized by linearity, and the damping is determined based on linear principles. This pertains to the vertical displacement of the frame nod movement as well as the counter roll and oscillatory movement of the wheel. In this way, the car body space vibration has 5 degrees of freedom, namely, side swing, roll, head, nod, float and sink; each frame has 4 degrees of freedom, side roll, head and sink (ignoring nod); 2 degrees of freedom for each wheel with opposite swing and head, so there are 21 degrees of freedom for each four-axis vehicle and each six-axis locomotive of 25 degrees of freedom. Passenger car vehicles and locomotives are calculated according to the two-series spring. The displacement relationship of the vehicle and the box girder is introduced, which is also fully applicable to the truss section.

$$\Delta d_{s1} = X_{gq} - h_3\delta_{gq} + L_1\gamma_{gq} - X_{s1} - \frac{h_4}{B}(V_{r1} - V_{l1}) \tag{9}$$

When the wheel moves to the right (or left) from its centre position, the normal reverse force of the left and right rails to the left and right wheels is different, and the lateral force of the normal force is also different on the left and right wheels. The synthetic transverse force on the left and right wheels restores the wheel pair to the original middle position, see Equation (10). The magnitude of the lateral resilience is related to the transverse movement of the wheel and the load. If the dynamic load, suspension deformation force and creep force are excluded and the higher order trace is omitted, the lateral reaction forces exerted by the rail on the left and right wheels are as follows:

$$V_{fd\ 2} = \Delta d_{s1} C_{dx} + \Delta d_{ds\ 2} C_{dx} + \Delta d_{ds\ 3} C_{ds} + \Delta d_{ds\ 4} C_{dx} \tag{10}$$

In general, only when used, it can be approximately considered as linear, as shown in Equation (11).

$$U_{eu\ 2} = kx + \frac{1}{2} K_{ux} (\Delta_{uq}^2 + \Delta_{uh}^2) + X_c - h_l \gamma_c - L\gamma_c \tag{11}$$

The linear structure bearing arbitrary dynamic load is usually analysed by vibration type superposition method. This method is easy to calculate, can see the contribution of each order of the system; and can increase the type to be calculated; the physical concept is clear. However, it is based on the superposition principle, and the Equation (12) is only applicable to the vibration analysis of linear systems.

$$U_{ed\ 2} = \frac{1}{2} K_{dx} \Delta^2 ds_1 + \frac{1}{2} K_{dx} \Delta^2 ds_2 + \frac{1}{2} K_{dx} \Delta^2 ds_3 + \frac{1}{2} K_{dx} \Delta^2 ds_4 \tag{12}$$

For the time-range dynamic analysis of the nonlinear structure, the most effective method is the stepwise numerical integration method. This method divides the time course of the reaction into very short, equal, or unequal time periods. Within each designated time interval, the system attributes, including mass, stiffness, and damping, are presumed to remain invariant. However, these system attributes exhibit variations across distinct time intervals. Broadly speaking, the attributes of each time interval converge to those observed at the onset of said interval. Consequently, the vibrational differential equation characterizing the system within each time frame manifests as a linear differential equation with constant coefficients. The system response at the starting point of the time period is the initial vibration condition of the system in the time period, thus solving the response of the system at the time period end, so that the system vibration calculation within the time period is completed. From the beginning of loading, the vibration of the system in each period is calculated in turn, and the vibration response process of the nonlinear system is obtained, and the whole process of the nonlinear vibration of the system uses a series of successively Linear vibration to approximate. Obviously, the step-wise integration method is also applicable to the vibration calculation of the linear system. At this time, there is no need to calculate the characteristics of the system in each time period, and the calculation process is greatly simplified [25, 26].

Upon the passage of the train over the bridge, it induces vibrations within the axle system, typically characterized as linear micro-vibrations. Nonetheless, owing to the dynamic motion of the vehicle mass coupled with the involvement of the vehicle's spring and shock absorber mechanisms, the attributes of mass, stiffness, and damping within the axle system undergo rapid alterations. As a result, the vibrational equation governing the axle system manifests as a linear differential equation with variable coefficients. This equation also cannot be solved accurately, and is generally solved by the stepwise integration method.

3 Vibration Analysis of Axle System of Steel Truss Bridge

3.1 Analysis of Dynamic Characteristics of the Bridge

In the railway operation of the period, the train speed is low and the railway bridge is not very long. Although the train derailment has occurred under the action of earthquake load, it has not attracted enough attention. At that time, the railway engineering community was mainly concerned with the seismic problem of Bridges, and the contribution of running trains to the bridge seismic response was generally not considered. In the construction of high-speed railway, in order to ensure the smooth comfort and stability of the line, the bridge built for several kilometres or even ten kilometres, with the bridge instead of the road. In this way, the chance of the train being on the bridge when the earthquake occurs greatly increases. In addition, China is a multi-earthquake country, earthquakes often occur. For example, earthquakes in Tangshan are felt from time to time. Due to the frequent occurrence of light earthquakes, the time proportion of trains on the bridge has increased accordingly, and due to the high speed, high density, and fully closed operation of high-speed railway, the speed of trains is very fast, so the movement of trains on the bridge becomes very important [27, 28]. Once the derailment in the earthquake will endanger the life safety of passengers and bring great property damage. Therefore, the study of the previous studies, the majority of researchers study bridge coupling dynamic interaction without the effect of earthquake, Figure 2 study the effect of the bridge on the action of the train, even considering the movement of the train as the bridge movement system known condition or boundary conditions, or in the analysis of the vehicle to a single load or load column to study the seismic response law

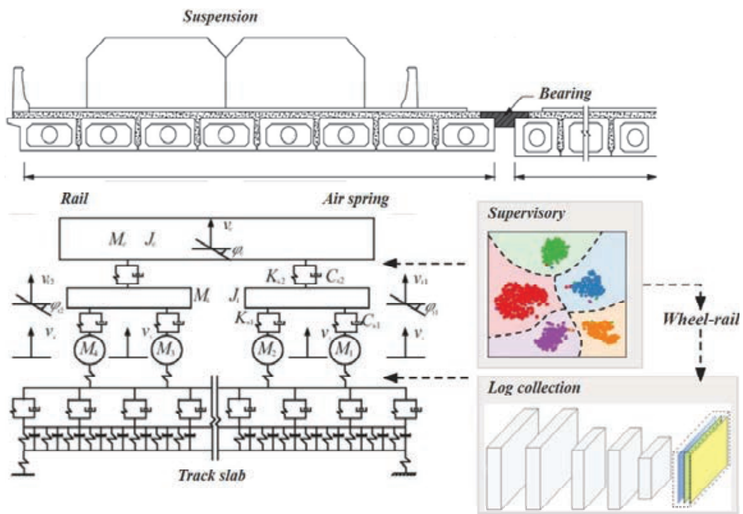

Figure 2 Coupling diagram.

of the bridge. In recent years, the movement of train under earthquake. This paper studies the stability analysis, the dynamic behaviour of the vehicles and the safety of vehicle walking.

Bridge coupling vibration analysis considering earthquake calculation and traditional bridge seismic calculation is different, the traditional bridge seismic is to check the bridge structure under earthquake will be damaged, namely from the aspects of internal force, strength, stability to measure whether bridge structure meet the requirements, so the seismic calculation generally focus on the relative displacement of the structure. Earthquake axle coupling vibration analysis is to analyse the train running safety and ride comfort, which needs to be evaluated from three aspects: absolute displacement, absolute speed and absolute acceleration. Consequently, it is imperative to account not merely for the foundation's acceleration but also for its velocity and displacement. The vibration analysis model pertaining to the seismic load off-bridge coupling system conceptualizes the train and the bridge as an integrated system. It identifies track irregularities as the inherent excitation source, while employing seismic loads as external excitations acting upon the bridge support. The motion equation of the whole axle system is divided according to the non-support node and the ground support point, and the motion equation of the axle system under the action of earthquake when different ground motion incentive is applied at each support.

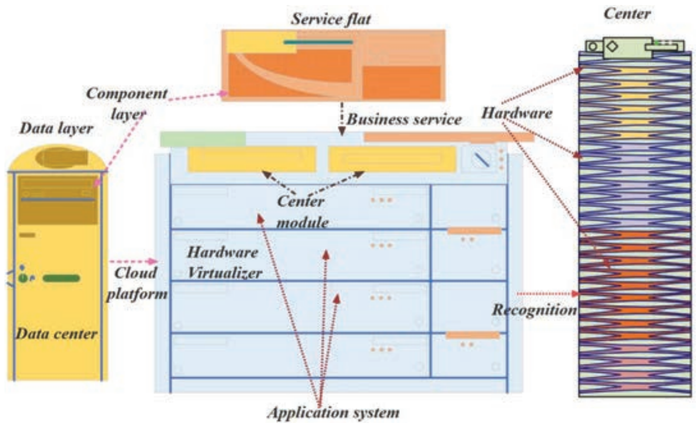

Figure 3 Vibration optimization diagram.

3.2 Analysis and Evaluation of Axle Vibration

In the computation related to axle coupling vibrations under seismic conditions, beyond merely accounting for the duration of seismic acceleration, one must also incorporate the durations associated with ground motion speed and displacement [29, 30]. However, because the current seismic records generally only provide acceleration information the seismic wave data obtained is mostly given in the form of acceleration time course. Synthetic artificial seismic waves also only generate acceleration wave information. Therefore, the ground motion velocity and the displacement time course need to be obtained by integrating the seismic acceleration data. However, drift occurs if the displacement time course is obtained by direct quadratic integration of the acceleration time span. This is because in the acceleration time synthesis calculation, although some correction methods (such as zero-line correction method), some long period components will still remain. Figure 3 Although they do not cause the drift of the acceleration time, they will cause serious drift in the displacement time course after integration. Computing with such a displacement time course will lead to a distortion of the calculation results. Many scholars have studied this extensively and believe that a small number of long period components in the acceleration time course is the main cause of the displacement time course drift. Therefore, how to filter out these long-period components is the key to solve this problem.

Building upon prior investigations concerning the time-domain optimization correction algorithm, we employ the least squares method for acceleration correction. Subsequently, the corrected acceleration undergoes double integration to derive both the velocity-time profile and the displacement-time profile. After comparing a large number of integral displacement time-course curves, according to the standard of the mean line and the cubic polynomial as the mean line of acceleration. In this way, subtracting the corresponding cubic polynomial mean line fitted by the least squares method in the input acceleration time course can not only eliminate the non-zero drift value from the root and facilitate the application of engineering, but also avoid the damage of the integral relationship between acceleration, speed and displacement after only high-pass filtering of the integral displacement.

4 Study on the Influence of Seismic Wave Strength on the Dynamic Response of Continuous Steel Truss Bridge

The assessment of a bridge's dynamic characteristics serves as a foundational step in understanding its dynamic behavior, with its inherent vibration properties dictating its dynamic response attributes. Within the realm of structural dynamics analysis, spontaneous vibration frequency and damping emerge as pivotal metrics for delineating a structure's dynamic traits. By evaluating the self-vibration frequency of the bridge, one can ascertain the validity of the bridge's computational model, alongside ensuring the accuracy of both the stiffness and mass matrices. Additionally, parameters such as the integration time step (r) in the incremental integration method and the bridge's damping characteristics are determined using the Rayleigh damping matrix methodology. Consequently, the precise determination of the bridge's self-vibration frequency assumes paramount importance. Within the context of this study, the steel bridge deck collaborates with the primary truss, with considerations excluding the stiffness attributes of the ballast groove and the bridge slab. Consideration of constant load: 1 constant, the main truss and railway bridge panel are 228 weight, kN/m, 335 kN/m; 2 constants, the second constant load of concrete ballast trough, ballast and track structure is 190 kN/m, and the second constant load of highway bridge deck pavement is 85 kN/m. The accuracy of the outcomes is intrinsically correlated with the integrity of the model. Emphasis should be placed on the simulation of structural stiffness, mass and boundary conditions. Therefore, in establishing the calculation model of the bridge structure, the following principles are mainly followed: the types of units and the real constants should reproduce the real mechanics and physical characteristics of the structure as much as possible; the connection between the independent parts of the structure should be simulated as much as possible; the boundary conditions of the

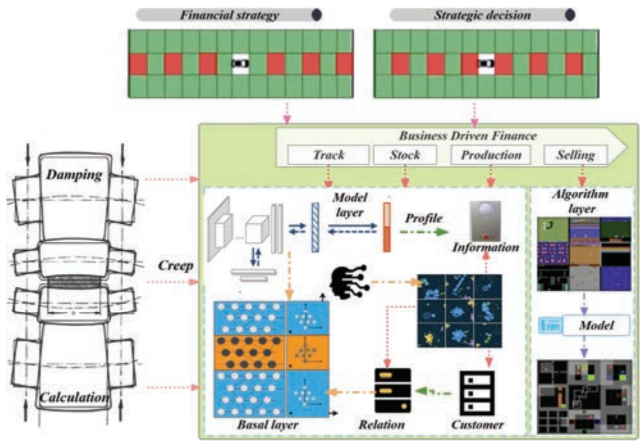

Figure 4 Comfort evaluation diagram.

whole system and the outside world should be as accurate as possible; the establishment of the model should fully consider the principal contradiction and discard the minor and irrelevant parts, so as to improve the calculation speed.

Following these principles, when establishing the model of the bridge, the steel truss beam is modeled with the finite element, the plane rectangular unit is discrete, the space beam unit is discrete, and the schematic diagram of the finite element of the whole bridge structure is scattered, as shown in Figure 4. There is a difference between the smoothness of the vehicle vibration and the comfort level. The stability of the vehicle vibration is to determine the vehicle itself, and the vehicle comfort refers to the evaluation of the influence of the mechanical vibration of the vehicle on the passenger. China, Germany and other countries use Spalin comfort and stability indicators W to assess vehicle comfort and stability. In accordance with the "Code for Dynamics Performance Assessment and Test Identification of Railway Vehicles (GB5599-85)," the operational stability of passenger cars, specifically pertaining to passenger ride comfort, is evaluated based on criteria such as the stability index and the average maximum vibration acceleration.

5 Experimental Analysis

In order to study the traveling effect of seismic wave on the train, the transverse seismic wave intensity was normalized according to 0.05 g, 0.1 g,

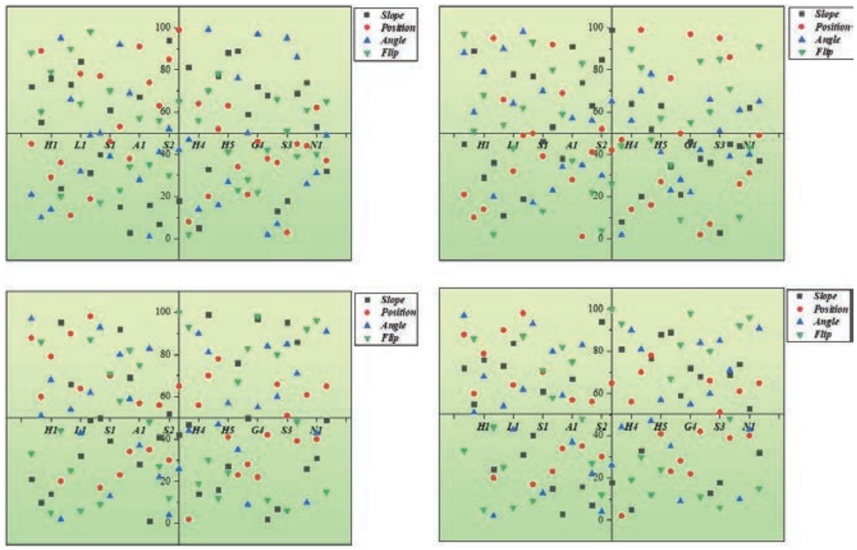

Figure 5 Stereo diagram of the vibration intensity diagram.

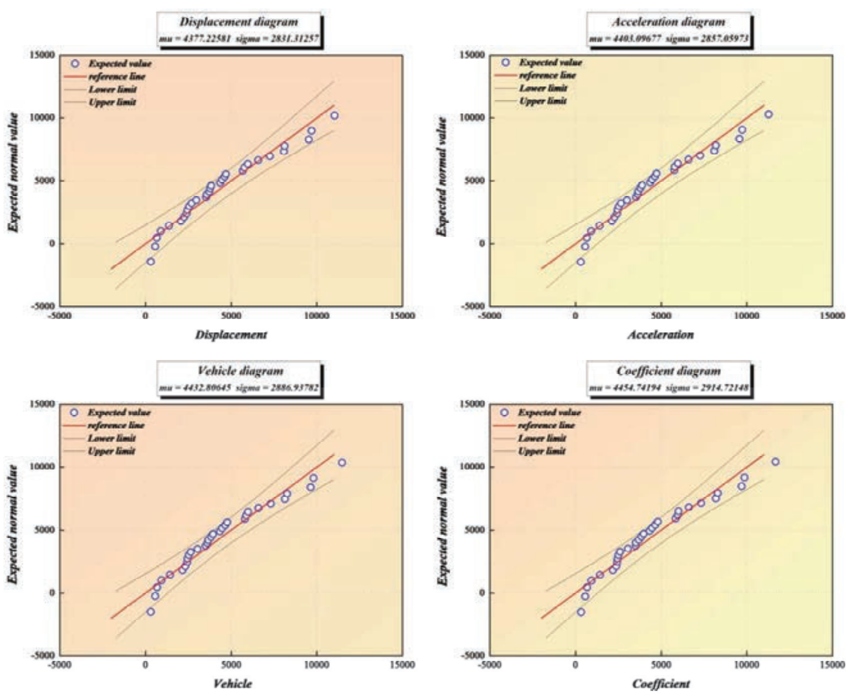

Figure 6 Vibration distribution diagram.

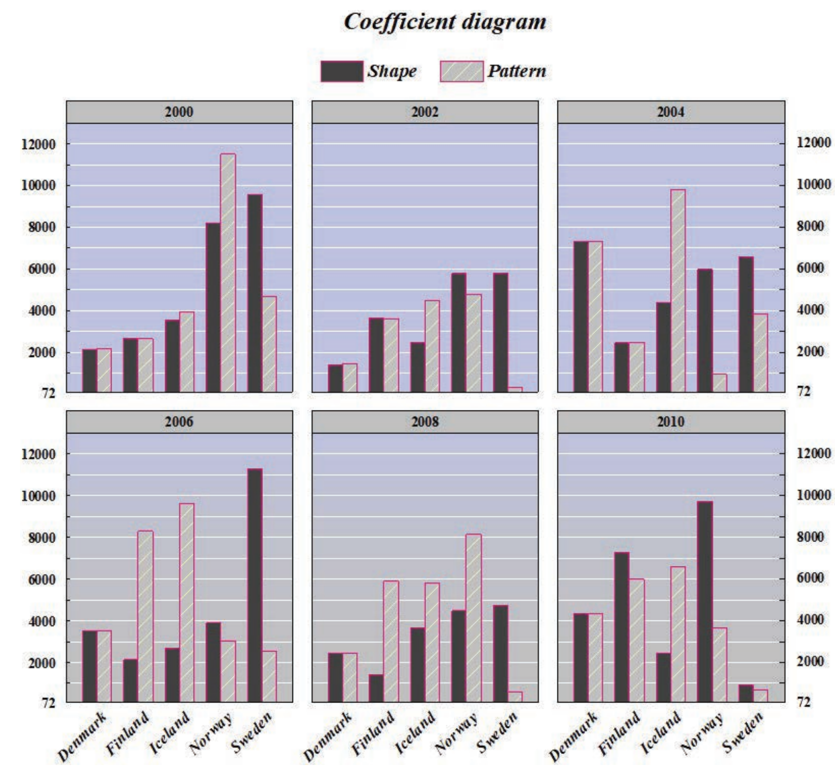

Figure 7 Derail curve diagram.

0.15 g, 0.2 g, 0.25 g, 0.3 g to calculate the dynamic response of the train at 300 km/h, and the traveling behavior of the train was studied. The relationship between seismic wave strength and transverse displacement, transverse acceleration, vertical acceleration, train derailment coefficient, wheel load reduction rate, transverse wheel and rail force, transverse acceleration and vertical acceleration of car body. Figure 5 shows the corresponding change regularity curves.

In order to study the influence of vertical seismic waves, the influence law of vertical seismic waves is simulated. The speed of the simulated vehicle in the calculation is 300 km/h, changing the amplitude of the vertical seismic wave. The results are shown in Figure 6.

In order to study the influence of train speed, the seismic wave intensity is constant and the movement of the train is studied by changing the speed of the train. To facilitate analysis and comparison, the relationship curve of maximum vertical displacement, maximum acceleration, maximum vehicle acceleration, derailment coefficient and vehicle speed change in the bridge deck span is shown in Figure 7.

6 Conclusion

(1) Under the action of no earthquake, when the Japanese E500 power dispersed independent high-speed train passes the bridge at a speed of 250$\sim$350 km/h, the Sperling comfort index is less than 2.66, and the ride comfort of the train is more than "good".

(2) Under the action of small shock, the maximum lateral displacement of the bridge is 18.30 mm, the maximum vertical displacement of the bridge is 12.30 mm, the maximum lateral acceleration is 0.73 m/s^2 $<$0.15 g, and the maximum vertical acceleration is 1.22 m/s^2$<$0.35 g. Compared with the action of no shock, the bridge response has a large increase. Despite this, the bridge response still meets the requirements. The derailment coefficient and the load reduction rate of the train do not exceed the limit, but the values are relatively large, so the train safety can be guaranteed, and the ride comfort of the train is qualified.

(3) Under the action of medium shock, the transverse displacement of the bridge reaches 124 mm, the maximum vertical acceleration is 5.16 m/s^2$>$0.35 g, and the bridge response has exceeded the limit. The train derailment coefficient also exceeds the limit. Therefore, it is unsafe for trains to walk on the bridge under the action of medium shock.

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