# Comparative analysis for bridge vibration of Shinkansen viaducts based on different track irregularity spectra


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## 1. INTRODUCTION

With the rapid economic and urban development, the high-speed railway connecting the major cities is becoming a new trend of railway development in the world due to its high speed, comfort, punctuality, safe running, high transportation capacity and less land use. Since the Tokaido Shinkansen as the first high-speed railway was began operations in Japan in 1964, many countries such as China, France, Germany, Italy, Spain, etc., have developed the high-speed railway. The total distance of high-speed railway is shown in Fig. 1 especially in operation increased to 21365km in the world[1]. In China, the percentage of bridge length in the Beijing-Tianjin Inter-city high-speed railway is as high as 87.7%. In Japan, the average percentage of Shinkansen viaducts is 48%, and this value is continuously increasing. They usually pass directly over densely populated urban areas and then cause some long-term bridge vibration problems. Track irregularity is an important interference source of bridge vibration and one of the main factors to control the highest speed of train. The strong bridge vibration can not only directly influence the working state and serviceability of the bridge, but also reduce the train traveling stability, comfort and safety. Whether good track irregularity can be obtained or not is one of key problems to determine the high-speed railway success or fail. Regarding this topic, the past research works mainly divided into two kinds[2-5]. One kind was the established track irregularity spectra, studying the influence of train-bridge interaction (TBI) system with different time samples. Other kind was different track irregularity spectra, but only studying the influence of dynamic property of train. Therefore, it is very necessary to investigate the dynamic property of TBI system due to the track irregularity for directing the designing, construction and maintenance of high-speed railway.

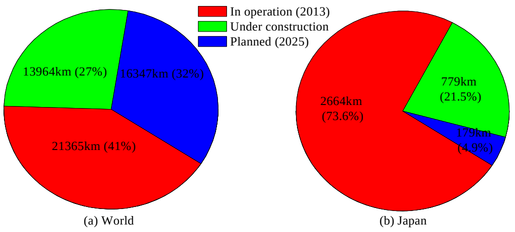

**Fig. 1** Route kilometers of high-speed railway

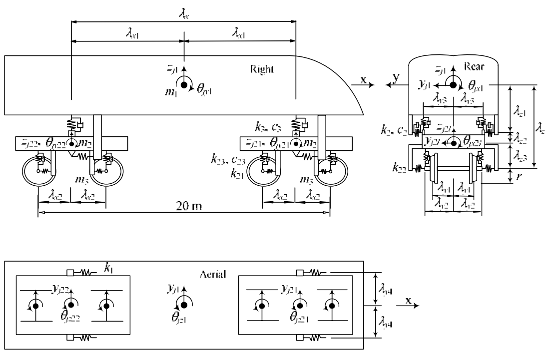

**Fig. 2** High-speed train model

In this study, in order to further investigate the influence of dynamic property of the TBI system based on different track irregularity spectra, taking German high disturbance, low disturbance and Japanese track irregularity spectra of high-speed railway as comparative objects, the differences among three kinds of track irregularity power spectral density (PSD) were analyzed and the time samples of three kinds of spectra were obtained with the frequency domain method.

## 2. ANALYTICAL MODELS

### 2.1 High-speed train model

The high-speed train is composed of 16 cars. Each car is modeled as 15 DOFs system shown in Fig. 2, assuming that the train is running on a straight line at a constant speed; the wheelsets remain in contact with the rail at all times; the car body, the bogies and wheelsets are rigid bodies; they are connected to each other three-dimensionally by linear springs and dampers. In this train model, the sway, bouncing, pitching, rolling and yawing motions of the car body, and the sway, parallel hop, axle windup, axle tramp and yawing motions of the front and rear bogies are taken into account. Each car is treated as independent dynamic system without modeling the coupling device. It can appropriately express the vertical and lateral dynamic responses of the TBI system.

### 2.2 Shinkansen viaducts model

The Shinkansen viaducts which are the typical reinforced concrete viaducts in the form of a rigid portal frame are adopted in this analysis. The cross section and dimension details are shown in Fig. 3. The viaducts are built with 24m length bridge blocks which are separated with each other and connected only by rail structure at adjacent ends. Each block has three 6m length center spans and two 3m length cantilever girders, so called hanging parts, at each end. Three blocks of the bridge are adopted for the analysis and are modeled with

3D beam elements as shown in Fig. 4. Thus the connecting effect of the rail structure and the influence of train's entering and leaving can be naturally taken into account. Double nodes defined as two independent nodes sharing the same coordinate are adopted at the pier bottoms to simulate ground spring effect and between the rail and slab to express the elastic effect of the sleeper and ballast. Rayleigh damping is adopted for the structural model and the damping constant of 3% is assumed for the first and second modes of the structure according to past field test results.

## 3. TRACK IRREGULARITY SPECTRA

In general, the actual measured track irregularity record is necessary if a simulation is expected to give a real response result and capture the influence of track irregularity. However, such a record is not always available for high-speed railway considered in a simulation. Another solution is to use the PSD function for the track geometry in the frequency domain to represent the track irregularity. Therefore, the PSD functions of German and Japanese track irregularity of high-speed railway in both vertical and lateral directions were considered to analyze the influence for TBI system.

### 3.1 German track irregularity spectra

German track irregularity spectra which are composed of high disturbance and low disturbance of track irregularity spectra are considered. Low disturbance is suitable for the high-speed railway allowable velocity above 250km/h. High disturbance is suitable for general railway. The German PSD functions of track irregularity in both vertical and lateral directions are adopted as Equations (1) and (2), respectively.

$$S_V(\Omega) = \frac{A_v \cdot \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} \quad \mathrm{m^2/(rad/m)} \qquad (1)$$

$$S_a(\Omega) = \frac{A_a \cdot \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} \quad \mathrm{m^2/(rad/m)} \qquad (2)$$

In which, $\Omega$ (rad/m) indicates the spatial circular frequency of the track irregularity; $\Omega_c$, and $\Omega_r$ (rad/m) are the cut off frequency; $A_v$ and $A_a$ ($\mathrm{m^2 \cdot rad/m}$) are the roughness constant. The values of the cut off frequency and the roughness constant are shown in Table 1[5].

### 3.2 Japanese track irregularity spectra

Japanese track irregularity spectra proposed by Akio Matsuura[4] are considered to comparative analysis with German track irregularity spectra. The PSD functions of track irregularity in both vertical and lateral directions are given in Equations (3) and (4) respectively.

$$S_V(f) = \frac{2 \times 10^{-9}}{f^3} \quad \mathrm{m^2/(1/m)} \qquad (3)$$

$$S_a(f) = \frac{10^{-9}}{f^3} \quad \mathrm{m^2/(1/m)} \qquad (4)$$

In which, $f$ (1/m) indicates the spatial frequency of the track irregularity.

### 3.3 Comparison of PSD functions

According to above PSD function equations, the values of PSD with different wavelength range can be obtained. Three

**Table 1** Cut off frequency and roughness constant

| Track grade | High disturbance | Low disturbance |
|---|---|---|
| $\Omega_c$/(rad/m) | 0.8246 | 0.8246 |
| $\Omega_r$/(rad/m) | 0.0206 | 0.0206 |
| $A_a$/($\mathrm{m^2 \cdot rad/m}$) | $6.125\times10^{-7}$ | $2.119\times10^{-7}$ |
| $A_v$/($\mathrm{m^2 \cdot rad/m}$) | $10.80\times10^{-7}$ | $4.032\times10^{-7}$ |

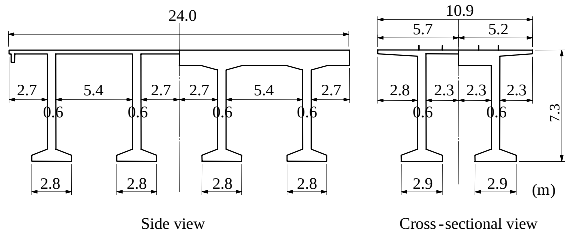


**Fig. 3** Dimensions of Shinkansen viaducts

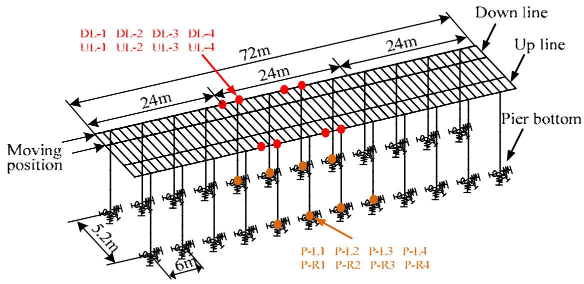


**Fig. 4** Shinkansen viaducts model

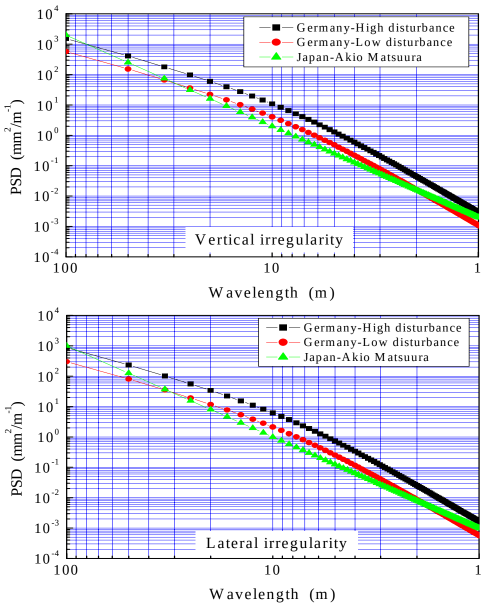


**Fig. 5** Comparison of three PSD curves

PSD curves including German high disturbance, German low disturbance and Japanese track irregularity in both vertical and lateral directions are shown in Fig. 5. The wavelength range big influencing on the bridge vibration of the TBI system is from 1m to 100m, which can satisfy the bridge vibration analysis requirement of the TBI system. In general, short wave components affect the running safety indices such as derailment factors and offload factors, while long wave components affect the car-body accelerations and the riding comfort of passengers.

From the figure, it clearly shows the wavelength properties of three kinds of spectra. For the vertical irregularity, German

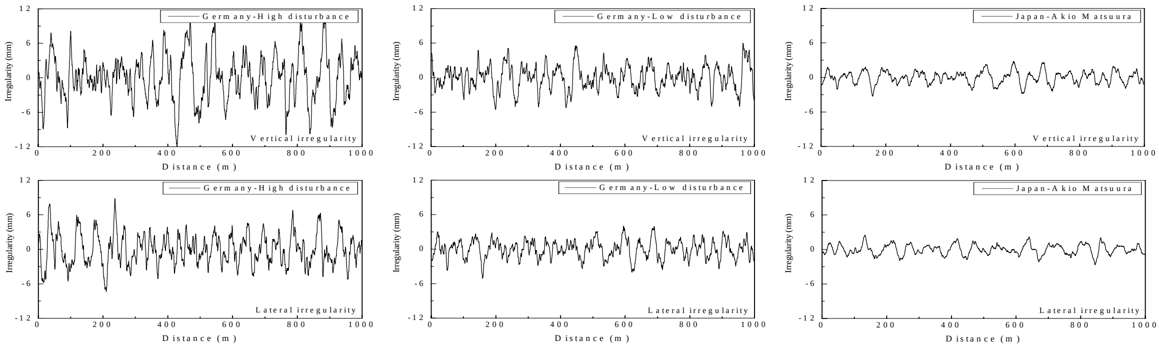


**Fig. 6** Time samples of three PSD functions for the right rail

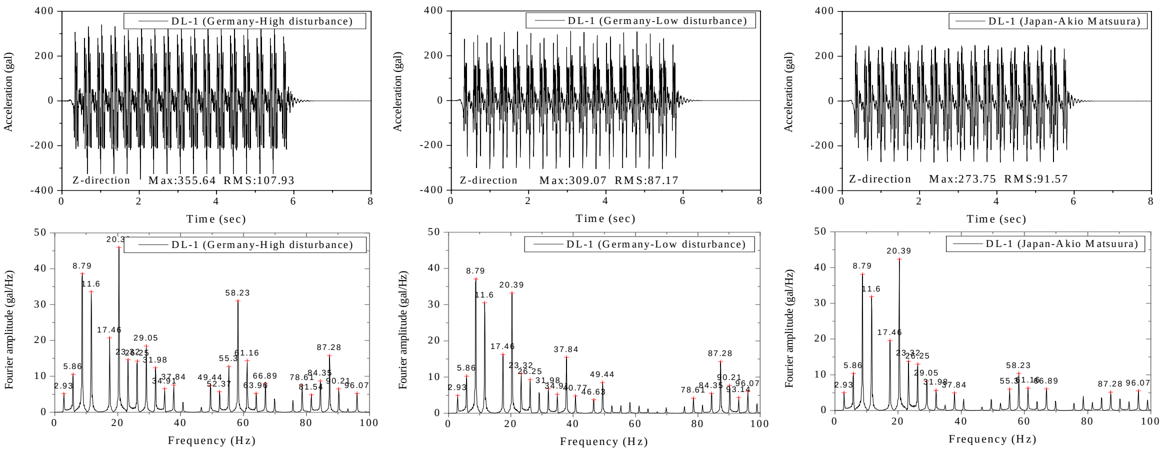


**Fig. 7** Comparison of acceleration responses of Shinkansen viaducts in the vertical direction

high disturbance is inferior to other two track irregularity spectra in the wavelength range from 1m to 80m. Japanese track irregularity is superior to those of Germany in the wavelength range from 2m to 30m. For the lateral irregularity, the total trend of track irregularity spectra is the similar with that of the vertical irregularity. But in the whole wavelength range, German high disturbance is the worst. Then, low disturbance is better than Japanese track irregularity in the wavelength range from 1m to 2m and from 30m to 100m.

### 3.4 Comparison of time samples

The stochastic process time samples were obtained by using the frequency domain method of PSD equivalency to simulate the track irregularity spectra[5]. The time samples of three PSD functions for the right rail are shown in Fig. 6. It shows the amplitude level of track irregularity.

For the vertical irregularity, the total trend is German high disturbance > low disturbance > Japanese track irregularity. These maximum amplitudes are followed by 12.02mm (11.15mm), 5.99mm (7.64mm) and 3.42mm (3.35mm) for the right (left) rail. For the lateral irregularity, the total trend is the same with vertical irregularity. These maximum amplitudes are followed by 8.83mm (9.36mm), 5.09mm (5.26mm) and 2.67mm (2.69mm) for the right (left) rail.

## 4. BRIDGE VIBRATION ANALYSIS

Considering three kinds of track irregularity spectra, the bridge vibration of Shinkansen viaducts under running high-speed trains at the speed of 262km/h was calculated by the computer program[6]. Newmark's $\beta$ step-by-step integration method was applied to solve dynamic differential equations. The time step in the numerical integral is set to 0.0005s. The acceleration and displacement responses of the hanging parts as the comparative objects were discussed to the influence of the bridge vibration of Shinkansen viaducts based on different track irregularity spectra.

The comparison of acceleration responses of Shinkansen viaducts in the vertical and lateral directions at the hanging part (DL-1) are shown in Fig. 7 and Fig. 8, respectively. Their maximum (Max) and root-mean-square (RMS) value together with the Fourier spectra are also indicated in the figures. The influence of track irregularity on the vibration acceleration of viaducts is bigger. Maximum accelerations under German low disturbance and Japanese track irregularity are significantly smaller than that under high disturbance. Comparing with German high disturbance, the maximum accelerations of low disturbance and Japanese track irregularity are decreased 13% and 23% respectively in the vertical direction, decreased 7% and 49% respectively in the lateral direction. It indicates that the vibration influence of lateral irregularity is larger than that of vertical irregularity and the difference of three kinds of spectra in the wavelength range from 2m to 30m just reflects the difference of bridge vibration. Frequency contents under German high disturbance are the similar with that under low disturbance and Japanese track irregularity, but only the amplitudes are a little different.

The comparison of displacement responses of Shinkansen viaducts in both vertical and lateral directions at the DL-1 are shown in Fig. 9. Maximum displacements of three kinds of

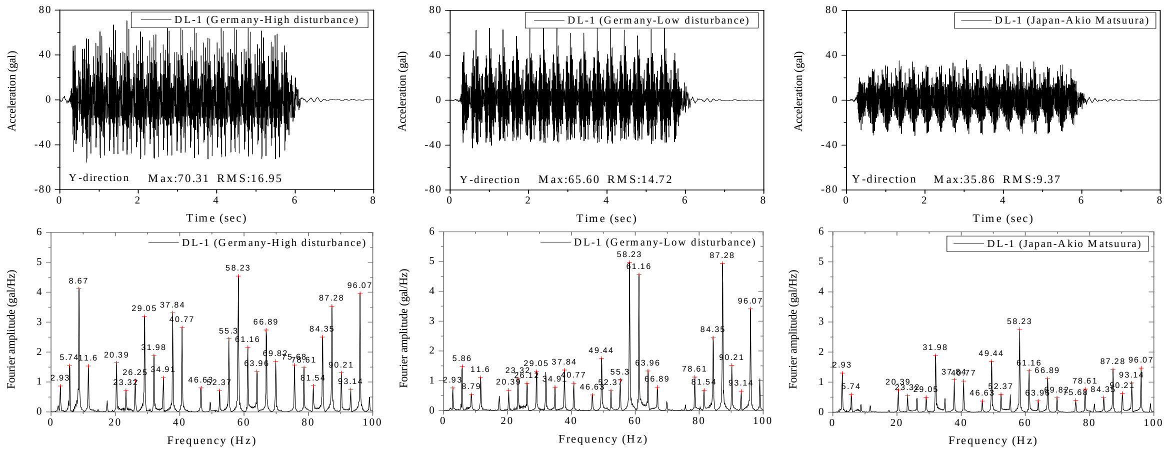


**Fig. 8** Comparison of acceleration responses of Shinkansen viaducts in the lateral direction

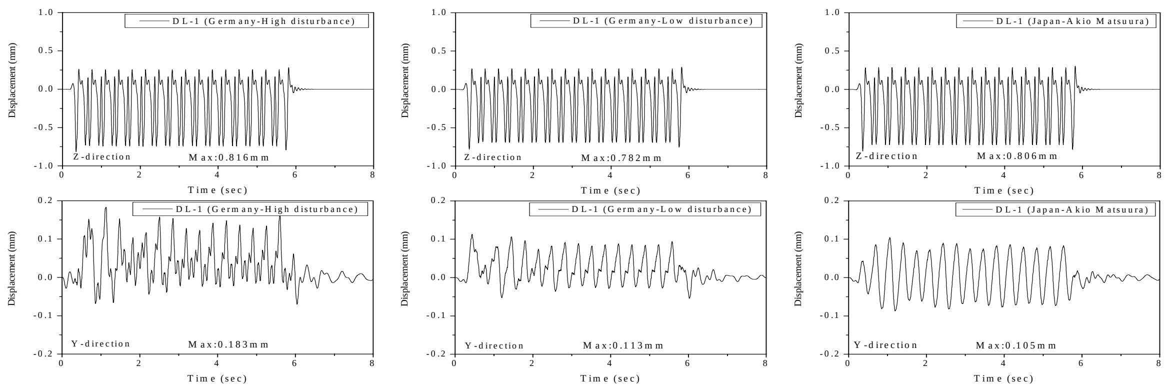


**Fig. 9** Comparison of displacement responses of Shinkansen viaducts

spectra are very close in the vertical direction, and that of German high disturbance are a little bigger. But the difference of maximum displacements in the lateral direction is a little bigger. The maximum difference is 4% and 42% in the vertical and lateral directions, respectively.

## 5. CONCLUSIONS

In this study, German high disturbance, low disturbance and Japanese track irregularity spectra of high-speed railway were comparatively analyzed and time samples were obtained by the frequency domain method. Numerical analysis of the bridge vibration was conducted with three kinds of track irregularities as the external excitations. The acceleration and displacement responses of the hanging parts were selected as dynamic indicators for comparison, the results are as follows.

(1) The influence of track irregularity on the vibration accelerations is bigger, and the vibration accelerations under Japanese track irregularity are significantly smaller than that under German high disturbance and low disturbance. The influence of lateral irregularity on bridge vibration is more obvious than that of vertical irregularity. But frequency contents under three kinds of spectra are the similar.

(2) The influence of track irregularity on the vibration displacement is very small in the vertical direction, and the displacement responses of viaducts are very close to under three kinds of track irregularity spectra. That is a little bigger in the lateral direction.

(3) Track irregularity is an important influential factor of bridge vibration of TBI system. Different track irregularity waves have different wavelength properties. The worse track irregularities are the larger vibration responses of viaducts will occur in both vertical and lateral directions. Therefore, Japanese track irregularity is better than German track irregularity. The improvement of track conditions is useful to safe operation and vibration reduction.

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