Feasibility verification for anomaly detection of track structures based on vibration data form vehicle body

Yuze Lv¹, Kun Zhang¹,* and Peigang Li²
¹School of Civil Engineering, Dalian Jiaotong University, Dalian, 116028, China
²School of Railway Transportation, Shanghai Institute of Technology, 201418, Shanghai, China
* Corresponding author’s e-mail: chinazhangkun@163.com

Abstract. Strengthening the detection and monitoring of abnormal track structure is of great significance to ensure the good operation of high-speed trains. The feasibility of detecting abnormal track structure of lower structure based on vehicle body vibration acceleration is verified numerically in this paper. A passenger car model is firstly established by rigid body dynamics software SIMPACK, and the vibration response of the car body is obtained by adding the abnormal irregularity waveform of typical track on the track spectrum as the wheel-rail excitation. And then, by comparing the acceleration vibration response of different positions and directions on the car body, the optimal measuring point of vibration sensor on the car body is determined. The results show that the vertical vibration acceleration of the front and rear position of the car can effectively reflect the abnormality of the lower track structure. Using the vibration data of the car body as the medium can provide a new way for the rapid abnormal detection of the lower track structure.

1. Introduction

Track irregularity is an important source of vibration excitation for locomotives and rolling stock, which directly affects the safety, stability and comfort of trains. Whether track ride comfort can be achieved is one of the core issues of high-speed railway. Therefore, it is necessary to strengthen the management of track geometry to ensure that the track maintains a good technical condition under high-speed driving conditions [1]. Existing motor vehicle and patrol vehicle mainly carry out geometric shape and appearance inspection for rails regularly. However, considering practicability and economy, motor vehicle and patrol vehicle can not detect and monitor rails in real time. It is of great engineering significance to find a new way to carry out research on rapid detection of abnormal irregularity of high-speed railway tracks.

In recent years, the research on track irregularity has attracted much attention. The existing research focuses on the analysis of the impact of track irregularity on the dynamic performance of vehicles, and begins to identify the lower track irregularity by the vehicle body vibration response as a medium. However, at present, the related research on the detection of track irregularity based on the test data on the carriage has not been carried out. Based on this, this paper establishes a passenger car model based on SIMPACK software, and uses the abnormal irregularity waveform of typical track as the wheel-rail excitation to compare the change law of the vibration acceleration measured from different location of the passenger car when passing through the abnormal track irregularity, so as to determine the optimal location of the vibration sensor on the car body, and preliminarily verify it. The
feasibility of detecting abnormal track structure of lower structure based on vehicle body vibration acceleration is discussed.

2. Establishment of passenger car dynamic model and track irregularity simulation

2.1. Establishment of passenger car dynamic model

Based on the multi-body dynamics software SIMPACK, a high-speed railway passenger car model is established in this study. In this model, the passenger car consists of front and rear bogies and each bogie has two wheelsets. The wheelsets are connected with the bogie through a suspension system (including a spring, a vertical shock absorber, a axle box spring, etc.). The secondary suspension system between the bogie and the carriage mainly includes a secondary air bomb including spring, transverse shock absorber, anti-snake shock absorber, etc. [2]. Figure 1 shows the model of the passenger car model.

![Figure 1. Model of the passenger car model established by SIMPACK software](image)

2.2. Random track irregularity simulation

All kinds of track irregularities existing on actual lines are superimposed by random irregularities of different wavelengths, phases and amplitudes, and are complex random processes related to line mileage. Statistical characteristics of track random irregularities can only be obtained by on-the-spot measurement of track, and can be expressed by power spectral density function (PSD). The relevant departments in Britain, the United States, Germany and China have carried out a lot of research work, and based on the measurement results, the expressions of track spectra for different lines are proposed. In this paper, the commonly used spectrum of German high-speed railway is used to simulate random track irregularity. The expressions of track irregularity, track direction irregularity and horizontal irregularity are expressed by [3]

\[
S_v(\Omega) = \frac{A_v \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)}
\]

(1)

\[
S_A(\Omega) = \frac{A_A \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)}
\]

(2)

\[
S_c(\Omega) = \frac{A_c b^{-2} \Omega_c^2 \Omega^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)(\Omega^2 + \Omega_c^2)}
\]

(3)

where \(b\) is half of the nominal rolling circle distance; \(v\) is the driving speed; \(\Omega\) is the spatial frequency; \(\Omega_c\), \(\Omega_r\) and \(\Omega_c\) are the spatial truncation frequencies, and their values are 0.8246\(\text{rad} \cdot \text{m}^{-1}\), 0.0206\(\text{rad} \cdot \text{m}^{-1}\) and 0.4380\(\text{rad} \cdot \text{m}^{-1}\), respectively; \(A_A\) and \(A_v\) are the interference level coefficients, and their values are 2.119\(\times 10^7\)\(\text{m} \cdot \text{rad}\) and 1.080\(\times 10^7\)\(\text{m} \cdot \text{rad}\) (for high-speed railways with speeds above 250 km/h), respectively. When the interference is high, the values are 6.125\(\times 10^7\)\(\text{m} \cdot \text{rad}\) and 4.032\(\times 10^7\)\(\text{m} \cdot \text{rad}\), respectively.
2.3. Anomalous track irregularity simulation

The track condition is one of the important factors affecting the comfort and safety of trains. Different types of track irregularities will have different effects on the running condition of trains at different speeds. However, investigations have shown that the various irregularity waveforms that appear to vary widely can be summed up into several types with similar characteristics [4]. Track irregularity not only has a wide range of wavelength changes, but also has different effects on different wavelength irregularities. Reference [3] classifies the abnormal track irregularity according to the wavelength type, and summarizes and describes in detail the wavelength range, vibration amplitude, characteristics and causes of various types.

In addition, the causes of track irregularity, the law of development and change, and the influencing factors are random and complex. Long-term field investigation and analysis of track structure and statistics of track structure anomalies show that typical local irregularity waveforms can be approximately described by some functional formulas, such as cosine, sine and exponential attenuation waveforms [13]. The cosine function is often used to simulate the corrugated wear on the top of the rail, the soft soil slopes and the uneven settlement of the foundation at specific locations of the track often lead to the local sinusoidal irregularity, and the track abnormalities caused by the difference of the stiffness of the foundation under the track at the locations of the local soft soil and the transition curves can be summed up as the local attenuation track irregularity [5,6]. In this paper, the cosine attenuation function is used to simulate the abnormal track irregularity. The specific waveform expression is as

\[ y = \frac{A}{2} \left(1 - \cos \frac{2\pi x}{l}\right) \]  

where \( A \) and \( l \) represents the amplitude of irregularity and the wavelength of irregularity. Here, the amplitude and wavelength of irregularity used in this study are 0.025 m and 30 m, respectively.

Because this paper mainly studies the vertical irregularity of the car body, only the abnormal irregularity waveform is added to the vertical irregularity excitation of the track, and the excitation generated by the random irregularity spectrum of Germany is used directly in the horizontal and vertical directions. The different waveform track irregularities are loaded on the track with a length of 1000m, and the passenger car is set at 250 km/h of speed to pass through the set track irregularity excitation. The data of vertical and lateral vibration acceleration are obtained from different positions of the car body to simulate the cases of different sensors place, and their abnormal changes are analyzed.

3. Analysis of simulation results

3.1. Vehicle body vibration data analysis under random track irregularity excitation

In order to verify the rationality of the established passenger car model, the random track irregularity spectrum of Germany is used as an external excitation to calculate the vertical and lateral accelerations at the center of the car box, as shown in figure 2.
Figure 2. Accelerations at center of carriage under excitation with random irregularity

From Figure 2, it can be seen that the amplitudes of vertical and transverse acceleration at the center of the carriage both are about 0.5 m/s², which is far less than the 2.5 m/s² limit stipulated in the Specification for the Test of High Speed EMUs. Moreover, it is close to the measured vibration acceleration of high-speed railway in References [3] and [7]. It can be seen that the whole train is running well and the established passenger car model is reasonable.

3.2. Vehicle body vibration data analysis under abnormal track irregularity excitation

In order to verify the feasibility of detecting abnormal track structure based on vehicle body vibration data, the abnormal track irregularity waveform of equation (4) is superimposed on the time history generated by the random track irregularity spectrum of Germany, and the excitation signal of the car body containing abnormal irregularity is simulated to excite the car body. Figure 3 shows the acceleration time histories of vertical and transverse vibration at the center of the car body, as well as at front and rear the carriage.

Figure 3. Acceleration at different locations of carriage under excitation with anomalous irregularity

From Figure 3(a), it can be seen that the vertical acceleration of the front, rear and center of the passenger car all change when passing through the irregular area of the cosine-shaped abnormal track. The vertical acceleration amplitude at the center of the car increases from 0.3 m/s² to the maximum...
value of nearly 0.9m/s², with a change of about three times. The vertical acceleration trend of the front and rear of the car is similar, and the vibration amplitude is from 0.7m/s² increased to a maximum of nearly 2.8m/s², with a change of about four times. From Figure 3(b), it can be seen that the lateral vibration acceleration of the front, rear and center of the carriage does not change significantly when passing through the abnormal section. The lateral acceleration of the front and back of the carriage is basically the same, and the vibration amplitude is larger than that of the center of the carriage. The above results show the vertical vibration of the car body can reflect the abnormal vertical irregularity of the track. The vibration accelerations of the front and rear ends of the carriage are more sensitive to the abnormal track than that of the center of the carriage, and so the front and rear ends of the carriage are ideal locations for vibration sensors.

4. Conclusions
A passenger car model is established by using multi-body dynamics software, and both the random irregularity and abnormal irregularity are used as excitation for simulation calculation and analysis. The results show that when a passenger car passes through a track with vertical abnormal irregularities, the lateral acceleration of the carriage changes little, while the vibration amplitude of the vertical acceleration at front and rear of the carriage increases significantly, which can effectively respond to the abnormalities of the lower track structure. Therefore, it can be concluded that it is feasible to detect abnormal track structure of lower structure based on vehicle body vibration acceleration. Using vehicle body vibration data as a medium can provide a new way for rapid abnormal detection of lower track structures.

Acknowledgement
Authors wishing to acknowledge financial supports from Science Foundation of Liaoning Province (20170540130), Research Foundation from the Education Department of Liaoning Province (L2014192), and Scientific Research Foundation for Introduced Talents of Dalian Jiaotong University.

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