Research on Semi-random Track

Irregularity of Straddle Type Monorail

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Abstract: The dynamic performance of straddle monorail train is closely related to the track irregularity. However, there is little research on the track irregularity of straddle monorail, and its semi-random particularity makes it impossible to use the existing track spectrum. In this paper, the irregularity of the running surface of prestressed concrete (PC) beam of monorail is measured, the altitude map is drawn, and the expression of the random irregularity of the track is obtained; the irregularity of finger-band and the deflection of PC beam under dead load are studied; a method is proposed to descript the semi-random track irregularity of straddle type monorail, the running surface of straddle monorail is reconstructed, and the correctness is verified by comparing with the test.

Keywords: straddle type monorail, running surface, track irregularity, semi-random,
1. Introduction

As a typical urban rail system, straddle type monorail is widely used in China. As the most important excitation, the accuracy of track irregularity seriously affects the analysis results such as stability, structural strength, safety and comfort[1].

The structure of straddle type monorail vehicle is very complex, each car has 4 running wheels, 8 guide wheels and 4 stability wheels, all of which are rubber tires; the track is composed of precast concrete (PC) beams, which are connected by finger-bands[2].

Because of the structure of the vehicle and the characteristics of the track, the description of the irregularity of straddle monorail cannot copy the rail or ordinary road. At present, the author has not found the relevant literature on the study of the irregularity of the track of straddle type monorail.

There has been a great deal of research on the irregularity of road or rail. In recent years, people have studied the use of new sensors and reconstruction of the irregularity, but have not mentioned how to describe the track irregularity with strong regularity, such as straddle monorail track. Ngwangwa et al.[3], Zhang Z. et al.[4], Cantisani et al.[5] studied the problem of obtaining road roughness and the mutual excitation between vehicle and road surface. Yuan Z. et al. [6], Kumar P. et al. [7], Han, W. et al. [8] studied the method of using laser sensor to measure road roughness. Cheli F. et al. [9], Mucka, P. et al.[10], Zhu Z. et al. [11] studied the coherent function model of track irregularity and the interaction
between track and train. Jiang Y. et al. [12], Lee CH et al. [13], Chen Z. et al. [14], Leng L. et al. [15,16] studied the algorithm and reconstruction of monorail track irregularity.

The irregularity of track is widely used in the research of straddle type monorail, these studies have used irregularity of road or rail, but no one discussed why and whether it is appropriate. Zhou J. et al. [17,18], Wen X. et al. [19], Du Z. et al. [20-22] studied the traction performance, curve passing performance, stability; structural strength safety and comfort of straddle type monorail train under the excitation of A-level road roughness. Lee C.H. et al. [23], Yulong B. et al.[24,25], Cai CB et al.[26], studied dynamic response analysis procedure for traffic-induced vibration of a monorail bridge and train.

In order to solve the problem of lack of expression method of irregularity for regular track, a solution is proposed, and the feasibility of the solution is verified by experiments.

2. Measurement of track irregularity

In order to obtain the first-hand data and provide support for the follow-up research, the author tested the inequality of the PC beams for straddle type monorail.

1) Measuring principle

In the test, non-contact method and laser rangefinder are used to measure the altitude of running surface of the PC beams. Fix the scanner on a bracket about 1.2 m high from the surface of the PC beam (Fig.1), measure the distance L and angle θ from the laser rangefinder to the points on the surface, and the coordinates of each point of the road surface of the PC beam can be obtained, see Formula (1), and the symbols can find in Table.1.
\[
\begin{align*}
\begin{cases}
x_{i,j} = l_{i,j} \sin \theta \\
y_{i,j} = l_{i,j} \cos \theta
\end{cases}
\end{align*}
\]

(1)

2) The irregularity test of the running surface of the PC beams

In this paper, the PC beams used in Chongqing Rail Transit Line 3 is measured in the PC beam depository in Yudong. 15 PC Beams were selected, each of which is about 22 meters long. The beams are supported at both ends and placed on the ground. According to ISO8608, the distance between adjacent data points is 0.15 m (x direction), then 147 data can be measured for each PC beam. The laser ranging sensor adopts LMS151 of SICK, with a measurement range of 0.5-50 m, an angular resolution of 0.25 ° and a statistical error of 12 mm (Fig.2)

Fig.3 is the data of several PC beams. It can be seen that the surface is relatively smooth, but its camber of the beam is obvious, the middle part protrudes about 32 mm compared with the two ends.

3. Calculation of track irregularity of straddle type monorail based on road spectrum

The author constructs a road with 7 PC beams (Fig. 4), which is 154 meters long and contains 1024 data points, like formula (2), where \( i \) is from 1 to 7.

\[
\begin{align*}
\begin{cases}
x_{i,n} = 0.15[147(i-1) + (n-1)] \\
z_{i,n} = z_{i,n} + (z_{i,147} - z_{i,1})
\end{cases}
\end{align*}
\]

(2)

According to ISO8608, the Power Spectral Density (PSD) of the road based on the spatial frequency \( \{ G_i(n_k), n_k \} \) is calculated, like the formula (3):
\[
\begin{align*}
&n = k, -7 \leq n \leq -5, -7 \leq k \leq -5 \\
&n = \frac{k}{3}, -5 \leq n \leq -2, -15 \leq k \leq -6 \\
&n = \frac{k}{12}, -2 \leq n \leq 1.75, -24 \leq k \leq 21 \\
&G_d(n) = \text{average}(G_d(j)), \frac{n_{j-1} + n_j}{2} \leq j \leq \frac{n_{j+1} + n_j}{2}
\end{align*}
\]

After curve fitting, the displacement PSD function of the road can be obtained (formula 4, Fig. 5). It belongs to A-class road.

\[G_d(n) = 1.08 \times 10^{-8} \times \left(\frac{n}{0.2806}\right)^{-0.719} \quad (4)\]

4. Study on the road profiles of straddle type monorail

It can be seen from Fig. 5 that there is a big pulse at the position of 0.045 m⁻¹, which is caused by the camber of the beam, if the influence of finger-band is considered, the pulse will be larger. However, when the displacement PSD function of the road is used, this characteristic is gone.

According to the particularity of straddle type monorail Road, its track profiles must contain the following elements: the irregularity of PC beam (excluding camber of the beam), the camber of the beam of PC beam, the span of PC beam, the clearance of finger band (in Fig.6), as shown in formula (5):

\[z(x) = q(x) + y(x) + f(x) \quad (5)\]

We can get \(q(x)\) from ISO8608, and will not be described here. \(y(x)\) is defined by formula (6), where \(w = 32\), \(f(x)\) is defined by formula (7)[27].

\[y(x) = \begin{cases} 
-w & \text{when } x \leq \frac{n - cl}{2} \\
0 & \text{when } x \leq (n = 1)l \\
\frac{2w}{l} & \text{when } x \leq \frac{n - 1}{2} \text{ and } x \leq (n = 1)l \text{ (when } x \text{ takes other values)}
\end{cases} \quad (6)\]
\[
\begin{align*}
100 \\
 f(x) = \begin{cases} 
 -10 & \text{when } \frac{n_l - u - d}{2} \leq x \leq n_l - \frac{d}{2} \\
 -10 & \text{when } n_l + \frac{d}{2} \leq x \leq n_l + \frac{d}{2} + u \\
 0 & \text{when } x \text{ takes other values} 
\end{cases} 
\end{align*}
\]

Based on formula (5), the 155-meter-long track was built, where \( q(x) \) is got according to A-Class pavement roughness, as shown in Fig.7.

5. Test verification

From 1:00 to 5:00 a.m. on October 27, 2017, a train test was conducted at Tongyuan Bureau to Longtousi Section of Chongqing Railway Line 3. The vehicle was loaded with counterweight to simulate AW3 working conditions, and the vibration acceleration of various points of the middle car was measured (Fig. 8). The sampling frequency of the accelerometer used in the experiment is 2000 Hz, and a relatively straight section of the line is selected for comparison. The travel distance is about 1000 m, and the travel time is 100 s.

In the simulation, the car body adopts the vehicle model of Chongqing line 3 (Fig.9), the parameters are shown in Table 2. For comparison, two simulations are carried out, among which the first simulation uses road spectrum only, and the second simulation uses the irregularity obtained in Fig.7.

As bogie is the most representative part of wheel rail contact, this paper, the vertical acceleration and FFT value at the center of front bogie of vehicle are compared. It can be seen that the results of the simulation using the ordinary road profiles only are quite different from the actual situation; however, the results are similar to the actual situation by using the track irregularity defined in formula (5), especially several characteristic
vibration frequencies are almost the same.

As can be seen from Fig. 10, if only A-level pavement spectrum is used for simulation, the vertical vibration of the train will be significantly less than the test. However, after adding the finger band and the camber of the track beam, the vertical vibration amplitude of the train calculated by simulation is almost the same as that of the test.

Fig. 11 is the frequency domain diagram of the vertical vibration of the bogie. It can be seen from the diagram that when the A-level road roughness is used (Fig. 11a), the vibration amplitude of the train bogie is very small, and the wave peaks at 2.01 Hz and 2.22 Hz correspond to the natural frequency of the bogie, this result is very different from the test. After adding finger plate excitation and track beamcamber, the first-order frequency calculated by simulation is 3.51 Hz, which is very close to the 3.60 Hz measured by test. It is proved that track irregularity is the main cause of vertical vibration of straddle monorail train, and the correctness of formula (6) is verified.

5. Conclusion

We use a statistical value to describe the irregularity of track and road, which can better reflect the random irregularity of the surface, but it ignores the regular irregularity of the surface, which causes a large error in the dynamic calculation of the surface with strong regularity. In this paper, taking straddle monorail as an example, a method of expressing track irregularity with strong regularity is proposed, and the feasibility of the method is verified by experiments. The conclusions are as follows:

1) It is proposed that track irregularity should be composed of random irregularity and regular irregularity, and the expression method of track irregularity of straddle monorail is
established.

2) The irregularity test of the running surface of PC beams used for straddle monorail is completed for the first time, and the random irregularity of the track is calculated; the periodic influence of the track such as camber of the beam and finger-band is studied, and the expression of periodic track irregularity is established.

3) The irregularity of the track of Chongqing Rail Transit Line 3 is reconstructed, and the dynamic simulation calculation is carried out. By comparing with the test, the correctness of the description method for the pavement unevenness of straddle type monorail is verified.

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**Biographies**

**Zhouzhou Xu** received the B.S. degree in Physics from Fudan University, Shanghai, China, in 2003 and the M.S. degree in mechanical engineering from Chongqing Jiaotong University, Chongqing, China, in 2011. He is currently pursuing the Ph.D. degree in Transport engineering at Chongqing Jiaotong University, Chongqing, China. His research interest includes vehicle dynamics and monorail vehicle.

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Fig. 1 Measuring Principle

- a. the laser ranging sensor
- c. the beam yard
- d. the test

Fig. 2 The Test
Fig. 3 the Altitude of some of the Track Beams

Fig. 4 the Combined Road
Fig. 5 The Roughness of the Roads

Fig. 6 The finger-band

Fig. 7 The irregularity of the track
Fig. 8 The test of the train

Fig. 9 the Vehicle Simulation Model
Fig. 10 Vertical vibration acceleration of the center of front bogie
Fig. 11 FFT of the vertical vibration acceleration of the center of front bogie

Table 1 Symbol

<table>
<thead>
<tr>
<th>symbol</th>
<th>description</th>
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<tbody>
<tr>
<td>$x_{ij}$</td>
<td>the abscissa of the jth point of the ith beam</td>
<td>$y_{ij}$</td>
<td>the ordinate of the jth point of the ith beam</td>
</tr>
<tr>
<td>$A_i$</td>
<td>the coordinate set of all the points of the ith beam</td>
<td>$z_n$</td>
<td>the altitude of the jth point of the nth beam</td>
</tr>
<tr>
<td>$G_d(.)$</td>
<td>Displacement PSD</td>
<td>$n_c$</td>
<td>the cth spatial frequency</td>
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</table>
\[ z(x) \quad \text{the altitude of the track at X coordinate}, \quad q(x) \quad \text{random irregularity of track} \]

\[ y(x) \quad \text{the influence of camber of the beam}, \quad f(x) \quad \text{the influence of finger-bands} \]

\[ w \quad \text{the maximum settlement of measured deflection under dead load}, \quad e \quad \text{the width of fingertip gap, } d \text{ is the length of interlaced fingers} \]

\[ l \quad \text{the span of PC beam}, \quad d \quad \text{the length of interlaced fingers} \]

<table>
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<tr>
<th>Project</th>
<th>Value</th>
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<tbody>
<tr>
<td>Body mass in AW3 (kg)</td>
<td>25800</td>
<td>running wheel mass (kg)</td>
<td>54</td>
</tr>
<tr>
<td>Bogie mass (kg)</td>
<td>5600</td>
<td>Guide wheel mass (kg)</td>
<td>30</td>
</tr>
<tr>
<td>Rotational Inertia of Body (l_{xx}) (kg(\cdot)m(^2))</td>
<td>43000</td>
<td>Vertical stiffness of running wheel (N/m)</td>
<td>120000</td>
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<tr>
<td>Rotational Inertia of Body (l_{yy}) (kg(\cdot)m(^2))</td>
<td>365000</td>
<td>Vertical Damping of Traveling Wheel (N(\cdot)s/m)</td>
<td>3400</td>
</tr>
<tr>
<td>Rotational Inertia of Body (l_{zz}) (kg(\cdot)m(^2))</td>
<td>365000</td>
<td>Radial stiffness of guide wheel (N/m)</td>
<td>980000</td>
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<tr>
<td>Rotational Inertia of Bogie (l_{xx}) (kg(\cdot)m(^2))</td>
<td>2400</td>
<td>Radial Damping of Guide Wheel (N(\cdot)s/m)</td>
<td>3120</td>
</tr>
<tr>
<td>Rotational Inertia of Bogie (l_{yy}) (kg(\cdot)m(^2))</td>
<td>3400</td>
<td>Vertical stiffness of air spring (N/m)</td>
<td>160000</td>
</tr>
<tr>
<td>Rotational Inertia of Bogie (l_{zz}) (kg(\cdot)m(^2))</td>
<td>9600</td>
<td>Longitudinal stiffness of traction rubber stack (N/m)</td>
<td>490000</td>
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