Comparison of wheel/rail dynamic responses of the rail weld zones between ballasted track and slab track in high-speed railways

Yichang Zhou, Kaiyun Wang*, Kaikai Lv

State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, People’s Republic of China

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Abstract

Both ballasted track and slab track are commonly used in high-speed railways. Based on the theory of vehicle-track coupled dynamics, the wheel-rail dynamic responses in the rail weld zones of these two tracks are investigated, and the $P_1$, transient high-frequency impact force, and the $P_2$, low-frequency impact force are analysed. The results show that, due to the high stiffness and small damping ratio of the vehicle and the ballasted track system, the $P_1$ force of the ballasted track is generally greater than that of slab track while the $P_2$ force is smaller than slab track. Furthermore, the duration of the impact load of ballasted track is longer than that of slab track. The results will provide a reference for the analysis and evaluation of ballasted tracks in high-speed railways.

Keywords: high-speed railways; weld zones; wheel-rail dynamic responses; $P_1$ and $P_2$; ballasted track; slab track.

1. Introduction

Modern slab track is mainly used in Chinese high-speed railways, while the alternative ballasted track is applied in some European countries. With the Beijing—Zhangjiakou high-speed railway being built in China, it is of great significance to analyse the wheel/rail dynamic interactions due to the rail weld irregularities in ballasted tracks. The rail weld zones are of key interest in both ballasted and non-ballasted tracks for high-speed railways. Repeated axle passages and large dynamic wheel-rail contact forces may result in propagating defects in the rail weld zones.

Many scholars have paid attention to this issue and carried out relevant research. Some recent advances in the rail corrugation were reviewed in the sixth session (CM2006) [1]. A series of rail weld irregularities measured on the Beijing—Shanghai high-speed railway passenger-dedicated line in China is presented in [2] and some typical theoretical models of the rail weld irregularity are established. By means of numerical simulations, characteristics of the wheel-rail dynamic interaction due to the rail corrugation are analysed [3-6] and influences of the corrugation wavelength and depth on the wheel-rail dynamic performance are investigated [7]. The wheel-rail dynamic interactions of high-speed Electric Multiple Units (EMUs) running on different types of ballastless tracks are compared in [8] and the results in the rail weld zones show that the difference is small. In view of this article, the slab track is selected as a reference to ballasted track.

Based on the vehicle-track coupled dynamics [9], the wheel-rail dynamic interactions of ballasted track and slab track are investigated using the theoretical rail weld irregularity model in this paper. The $P_1$ and $P_2$ forces when the EMUs pass through the weld zones of these two tracks are compared. Moreover, the effect of parameters of the rail weld irregularity model on the $P_1$ and $P_2$ forces are presented.

2. Wheel-rail dynamic research methods

2.1. Vehicle-track coupled dynamic models

Nowadays, the vehicle-track coupled dynamic model is widely used by researchers and railway organizations around the world to investigate the dynamic behaviour of railway train and track [10-13]. In order to compare the wheel-rail dynamic interactions of the rail weld zones and to analyse the characteristics of the $P_1$ and $P_2$ force, the vehicle-ballasted track coupled model and the vehicle-slab track model are established separately, as shown in Figs. 1-2.

In figure 1, the ballasted track sub-model is a so-called five-parameter model [14]. Both the left and right rails are treated as continuous Bernoulli–Euler beams which are discretely supported at the rail seats by three layers of springs and dampers, representing the elasticity and damping of the rail pad, ballast, and subgrade, respectively. In Fig. 2, the slab track
sub-model includes rail, rail fastening, and pad, track slab, cement-asphalt mortar (CA mortar), concrete base and subgrade, in which the rail fastening and pad, CA mortar and subgrade are considered as springs and dampers. Moreover, the concrete base and the subgrade are treated as a rectangular slab with continuous elastic support. In addition, the parameters of the vehicle CRH2 are adopted in this paper and the main parameters of the ballasted track and track slab are listed in Table 1.

![Figure 1. Vehicle-ballasted track coupled dynamic model](image1)

![Figure 2. Vehicle-slab track coupled dynamic model](image2)

**Table 1.** Main parameters of the ballasted track and slab track

<table>
<thead>
<tr>
<th>Track types</th>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballasted track</td>
<td>Stiffness of fastening system</td>
<td>60</td>
<td>MN/m</td>
</tr>
<tr>
<td></td>
<td>Damping of fastening system</td>
<td>50</td>
<td>kN·s/m</td>
</tr>
<tr>
<td></td>
<td>Ballast elastic modulus</td>
<td>110</td>
<td>MPa</td>
</tr>
<tr>
<td></td>
<td>Ballast vertical damping</td>
<td>58.8</td>
<td>kN·s/m</td>
</tr>
<tr>
<td>Slab track</td>
<td>Stiffness of fastening system</td>
<td>25</td>
<td>MN/m</td>
</tr>
<tr>
<td></td>
<td>Damping of fastening system</td>
<td>50</td>
<td>kN·s/m</td>
</tr>
<tr>
<td></td>
<td>Track slab elastic modulus</td>
<td>36000</td>
<td>MPa</td>
</tr>
<tr>
<td></td>
<td>CA mortar elastic modulus</td>
<td>200</td>
<td>MPa</td>
</tr>
</tbody>
</table>
2.2. The theoretical model of the rail weld irregularity

The traditional and theoretical model of the rail weld irregularity is adopted in this paper, as shown in Figure 3. There is an obvious concave form with the wavelength of $L_2$ and the depth of $a_2$, which is defined as the long wave in this paper. In addition, there is a mild form with the wavelength of $L_2$ and the depth of $a_2$, which is defined as the shortwave. Moreover, $L_2$ and $L_2$ are usually assumed as 1m and 0.1–0.2 respectively.

3. Wheel-rail dynamic interaction due to rail weld irregularities

In order to investigate wheel-rail interaction in the rail weld zone of ballasted track and slab track in the time domain, the wavelength and depth of the long wave are assumed to be 1m and 0.2mm while these of the shortwave are 0.2m and 0.2mm. When a high-speed vehicle runs on the ballasted track and slab track respectively, the simulation results of the wheel-rail vertical dynamic force of two tracks are shown in Figure 4.

![Figure 3. Rail weld irregularity model](image)

![Figure 4. Simulation results of wheel-rail vertical force in time domain](image)

At point A, the vehicle begins to enter the rail welded zone. Due to the concave of the top surface of the rail, the wheel-rail force slowly recovers to point B after a slight decrease when the vehicle passing the long wave zones of the weld. From point B to C, the vertical force first drops sharply and then rapidly increased to the maximum value. According to the definitions of $P_1$ and $P_2$ provided by Derby of Britain [15], this maximum force is called the $P_1$ force, which has a great influence on wheel-rail interaction, and another low-frequency peak is named the $P_2$ force, which plays a major role in the deformation and stresses in the track system.

Due to the excitation of the rail weld irregularity, the $P_1$ force of ballasted track is about 143 kN, which is higher than 134 kN for the slab track. However, the $P_2$ force of the ballasted track is 89 kN, which is smaller than 92 kN for the slab track. Furthermore, the vibration delay time of ballasted track is longer than that of slab track. Consequently, it is indicated that the wheel-rail dynamic interaction due to the rail weld irregularity in the ballasted track and the slab track is clearly different in high-speed railways.

4. Influence of parameters of the rail weld irregularity model on the $P_1$ and $P_2$ forces

For further investigation on the effect of rail weld irregularity on the $P_1$ and $P_2$ forces of the ballasted track and slab track, the different parameters of the irregularity model is applied. There are totally four parameters, in which the wavelength of the long wave is kept a constant saying 1 m assumed here. In addition, the running speed of the vehicle is always 250 km/h.

4.1. Influence of the depth of the long wave on $P_1$ and $P_2$

In this section, the values of wavelength and depth of the shortwave are designated as 0.2 m and 0.2 mm respectively, while a set of depth values of the long wave are assumed to be 0.1, 0.2, 0.3, 0.4 and 0.5 mm.

Influence of the depth of the long wave on $P_1$ and $P_2$ is shown in Fig. 5, in which BT_$P_1$ represents the $P_1$ force of ballasted track and ST_$P_1$ is the $P_1$ force of slab track. It can be seen that $P_1$ force of ballasted track is always larger than that of slab track with the increase of the depth of the long wave, and $P_2$ force is the opposite. When the depth of the long wave is raised from 0.1 to 0.5 mm, the difference of $P_2$ between ballasted track and slab track is approximately kept as 10 kN, and that of $P_2$ increases from 4% to 16%, which indicate that long wave depth of rail weld irregularity has an apparent effect on $P_2$.

![Figure 5. Influence of the depth of the long wave on P1 and P2](image)
4.2. Influence of the wavelength of the shortwave on $P_1$ and $P_2$

To investigate the influence of the wavelength of the shortwave on the $P_1$ and $P_2$ force, the value of the wavelength is varied while the other parameters are kept constant. The depth of the long wave and the shortwave are both set to 0.2 mm, and the wavelength of the shortwave varies from 0.1 to 0.3 mm.

The effect of the wavelength on the wheel-rail vertical force is illustrated in Figure 6. When the wavelength is shorter than 0.2 m, the $P_1$ forces of two tracks both decrease quickly with the growth of the wavelength. When the wavelengths are 0.15 and 0.20 m, there is a difference in the $P_1$ force. However, while the wavelength changes to 0.10, 0.25, or 0.30 m, the difference is small. With the increase of the wavelength, the $P_2$ force is relatively unchanged, with a small difference between the ballasted track and the slab track, which shows that the wavelength of the shortwave has little influence on the $P_2$ force.

4.3. Influence of the depth of the shortwave on $P_1$ and $P_2$

In order to expose the influence of the depth of the shortwave on the $P_1$ and $P_2$ forces, values of the depth of the long wave and the wavelength of the shortwave are fixed to 0.2 mm and 0.2 m respectively and the depth of the shortwave is varied from 0.1 to 0.5 mm.

Fig. 7 shows the variation of the wheel-rail vertical force versus the depth of the shortwave. As the depth increases, $P_1$ forces of both two tracks become gradually larger and the $P_1$ force curve of the ballasted track is always above that of the slab track. Meanwhile, the $P_2$ force of the ballasted track is smaller than that of the slab track and the $P_2$ forces are slightly affected by the depth of the shortwave. For example, when the depth increases from 0.1 to 0.5 mm, the $P_1$ forces of the ballasted track and the slab track raise 216% and 200% separately, and the $P_2$ forces of two tracks respectively increase 16% and 13%.

Figure 6. Influence of the wavelength of the shortwave on $P_1$ and $P_2$

Figure 7. Influence of the depth of the shortwave on $P_1$ and $P_2$

5. Conclusions

The influences of the rail weld irregularity of ballasted track and the slab track on the $P_1$ and $P_2$ forces are mainly investigated by simulation in this paper. It can be seen that the $P_1$ force on the ballasted track is always larger than that on the slab track and the $P_2$ force is opposite. In addition, the $P_1$ force is obviously affected by the shortwave of the irregularity while the $P_2$ force is mainly influenced by the wavelength of the long wave. Compared with the slab track, there is the higher stiffness and smaller damping ratio in the vehicle and ballasted track system, which causes the above situation. It is suggested that the further investigations on the influence of the stiffness and the damping ratio on the vehicle can be carried out.

Founding

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Disclosure statement

No potential conflict of interest was reported by the authors.
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