Prediction of wheel/rail rolling contact wear under the situation of wheel/rail vibration

Qian XIAO¹,², Chao CHANG¹, Jifeng ZHENG¹, Jiao FANG¹
¹. East China Jiaotong University Key Laboratory of vehicle operation engineering of Ministry of Education, Nanchang 330013, China;
². State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China.

Abstract: In order to predict the wear of wheel tread of high-speed train under the situation of wheel/rail vibration behavior, a multi-body dynamic model of vehicle and a finite element model of wheel/rail rolling contact are established. The nonlinearities of suspension system of vehicle, contact geometric and creep force of wheel/rail are considered in those models. The variation of longitudinal and transverse creep force between wheel and rail are analyzed by using numerical simulation and the wear of wheel tread is predicted by the evaluation method of wheel/rail wear based on the wear work. The results show that: wheel/rail contact positions and longitudinal creep force changing with time under the situation of vibration behavior of the wheel/rail. The larger lateral displacement of wheelset and the normal force wheel/rail are, the greater longitudinal and lateral creep forces in wheel/rail contact patch are. And wear of wheel tread is most serious in this condition resulting in out-of roundness of wheel. The periodic wear of wheel tread is affected by the coupling of periodic change of the wheelset lateral displacement and the wheel/rail force. This is the root cause of complex multistage wear of wheel tread.

Keyword: Wheel/rail vibration; High-speed train; Wheel/rail interaction; Transient finite element; Wear prediction

1 Introduction

In recent years, with the increasing of train speed, the wear of wheel tread is becoming more and more serious and the cycle of wheel reprofiling is gradually reduced. It not only increases maintenance and operation cost of train, but also has a serious impact on stability and safety of vehicle operation [1-2]. Study systematically on decreasing wear of wheel tread is necessary and many scholars have done a lot of useful research on it. Xu Liqun et al. [3] divided the wheel wear into three stages: rapid wear stage (early), wheel/rail relatively consistent stage (middle), weakened stage of self-regulation ability (late), and analyzed the law and reason of the wheel wear before and after the speed increasing. Ali Asadi and Mike Brown[4] analyzed and compared the effects of two different models of slip amount by using theory and experiment methods based on Archard wear model. The mild wear and severe wear are discussed. Analysis results show that the theoretical results and experimental results are close in wheel-flange contact, but the difference is nearly two times in tread contact. Chudzikiewicz[5] analyzed the prediction method of wear using tribology. Then, he studied the wear mechanism, which is applied to the rolling-sliding contact, and defined the wear area. In the analysis, he considers the track irregularity. The results show that the wear coefficient is determined by normal force in wheel/rail patch. In order to get an accurate result, the finite element method is adopted by more and more scholars. Li Xia [6] took wear of wheel rolling on the curve as the research object, the integration, comparison and analysis of wheel
wear superposition method are finished by integrating Archard wear model and vehicle/track coupling model. Chong Yi Chang [7] proposed the prediction method of wheel/rail wear based on three-dimensional finite element dynamic model. Three-dimensional finite element model was established with ABAQUS and wheel/rail wear was studied by numerical simulation. The wear of wheel/rail was calculated based on Archards wear model of the integral form of the micro area. Test results and numerical analysis results have good consistency. It is easily found that wheel/rail wear are mostly researched by direct measurement or numerical simulation. In those researches, the vibration and its effect on wear of wheel/rail didn’t be considered. However, during the rolling process, the vibrations exist in movements of wheel/rail. So, a vibration model and rolling contact transient model of high-speed wheel/rail are established, the wear analysis of wheel tread considering wheel/rail vibration behavior are done.

2 Dynamic analysis

The wheel/rail contact dynamic model of CRH2 shown in Fig.1., a high-speed train, is constructed with multi-body dynamics software UM. In this model, the nonlinearities of wheel/rail contact geometry, transverse backstop, anti-hunting damper and vehicle suspension are considered [8]. The dynamic analysis results are used to provide initial conditions for transient finite element model of wheel/rail rolling contact vibration.

Fig.1 The wheel/rail contact dynamic model of CRH2

The train speed is 300km/h and running time is 12s on the straight line. The instant speed, vertical force of wheel/rail, lateral displacement and the attack angle of wheelset are computed and their values tend to stable in 2s. Fig.2, Fig.3 and Fig.4 are curves of those values in 2s.

Fig.2 The curve of vertical force of wheel/rail

Fig.3 The curve of the attack angle of wheelset

Fig.4. The curve of lateral displacement of wheelset

As can be seen from Fig.2, the wheel/rail normal force is periodic vibration, which indicates that the wheel/rail rolling contact is accompanied by vibration. The maximum value of vertical force is 115751.8N and the minimum value is 688.4N, which are 193.8 times and 0.012 times for wheel/rail static loading respectively. The maximum vibration amplitude of the wheel attack angle is 1.568 mrad from Fig.3. The lateral displacement of wheelset is approximately periodic in Fig.4. It can be identified the lateral displacement of wheelset varies over a period of about 0.95s and the amplitude is 3.3 mm through comprehensive analysis.

3 Three-dimensional(3D) transient finite element model of high speed wheel/rail rolling contact

3.1 Transient finite element model of wheel/rail rolling contact

Using the real geometric of wheel/rail and elastic-plastic constitutive of its material, the 3D transient finite element model of wheel/rail
rolling contact is established with mixed Lagrangian-Eulerian method [9]. In this model, the line-speed of wheel is 300km/h and its angular velocity is 195rad/s. The size of smallest unit in the refinement area of rail is 2mm, and the length of the refinement area is 150mm. The 1/6 area of wheel is refined and the size of smallest unit is 2mm. The contact pair is defined as a limited slip surface to surface contact. And the contact surface of the wheel is set as the master surface, the contact surface of the rail refinement area is set to slave surface. The tangential contact characteristic is defined using penalty function method and the friction coefficient is 0.2. The normal contact is hard contact. The end and the bottom of rail are restricted fully. The axle of wheelset is defined as a rigid body and axle load is 15.4t. The elastic modulus and Poisson's ratio of wheel and rail are consistent with 205GPa and 0.3 respectively. The slope of rail is 1/40, the density of the wheel, rail and axle is 7800kg/m3. The relationship between the plastic strain and the true stress of the wheel/rail is shown in Fig.5.

The steady state analysis results of wheel/rail rolling contact are took as the initial condition of the transient finite element model. The explicit solution of the transient contact characteristics are achieved by ABAQUS/Explicit. The 3D transient finite element model of high-speed wheel/rail rolling contact is shown in Fig.6.

![Fig.6 The 3D transient finite element model of high-speed wheel/rail rolling contact](image)

### 3.2 The analysis of calculation results

The different contact parameters showed in Table 1 are from five special times in a cycle as initial conditions. Those instant times are about 0.2s, 0.5s, 0.66s, 0.84s and 1.1s according to Fig.4. The rolling time of wheel is 0.0015s with speed of 300km/h, so the forward distance is about 125 mm. The contact parameters at different times as the initial condition of the transient finite element model, the analysis results of the longitudinal and transverse creep force, the contact patch area of wheel/rail are shown in Table 2. According to Table 1 and Table 2, the variation of lateral displacement is periodic and longitudinal creep force changes regularly. Through analysis results of 0.2s, 0.66s and 1.1s, it can be found that the greater the wheel-rail normal force is, the longitudinal creep force and the contact patch area are also greater. Lateral creep force in 0.5s and 0.84s is greater than the other three times, and the contact patch area is less than the other three times. The main reason is the maximum lateral displacement in the two times. The influence of attack angle on longitudinal and transverse creep sliding force effect is not obvious.

![Fig.5 Curve of plastic strain and true stress](image)

### Table 1 The contact parameters of five special times

<table>
<thead>
<tr>
<th>times (s)</th>
<th>0.2</th>
<th>0.5</th>
<th>0.66</th>
<th>0.84</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelset lateral displacment (mm)</td>
<td>-0.035</td>
<td>-2.5</td>
<td>0.0013</td>
<td>3.3</td>
<td>0.002</td>
</tr>
<tr>
<td>Wheel attack angle (mrad)</td>
<td>-0.092</td>
<td>0.044</td>
<td>0.47</td>
<td>-0.32</td>
<td>0.24</td>
</tr>
<tr>
<td>Wheel/rail normal force (N)</td>
<td>74589.9</td>
<td>53853.8</td>
<td>69708.6</td>
<td>53529.5</td>
<td>50585.9</td>
</tr>
</tbody>
</table>
Table 2 Wheel-rail contact parameters and wheel contact patch

<table>
<thead>
<tr>
<th>time/s</th>
<th>0.2</th>
<th>0.5</th>
<th>0.66</th>
<th>0.84</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact spot shape</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>Contact spot area/mm²</td>
<td>202.5</td>
<td>198.9</td>
<td>228.0</td>
<td>188.9</td>
<td>208.8</td>
</tr>
<tr>
<td>Transverse creep force/N</td>
<td>1950</td>
<td>-2180</td>
<td>-1264</td>
<td>2050</td>
<td>-1290</td>
</tr>
<tr>
<td>Longitudinal creep force/N</td>
<td>12400</td>
<td>13900</td>
<td>11200</td>
<td>14200</td>
<td>12100</td>
</tr>
</tbody>
</table>

4 The wheel tread wear prediction with wheel/rail vibration

Wear work refers to the wear between wheel tread and the top surface of the rail within the unit time or the distance between the running unit. The wear work between the wheel and rail is commonly expressed by $W$. The product of creep forces and creep rate of wheel/rail will be defined to wear work in international, and its unit is $\text{N} \cdot \text{m}$ / $\text{m}$. The larger of wear work is, the more serious the wear of wheel/rail is. The formula of the wear work is as (1).

\[
W = \frac{\mu}{0.6} \cdot \frac{T_x + T_y}{A}
\]  

(1)

$\mu$ is the friction coefficient between wheel and rail, $T_x$, $T_y$ respectively is for the longitudinal and lateral creep force of wheel/rail contact, $v_x$, $v_y$ respectively is for the longitudinal and transverse creep rate of wheel/rail contact. $A$ is wheel-rail contact patch area. $0.6$ is the modified Kalker creep coefficient [10-12].

According to formula (1), the larger of the creep rate of the wheel/rail is, and the more serious of the creep is. That is to say, the more sliding component of the wheel on the rail, the greater the wheel-rail wear are.

Due to the left and right wheel contact parameters have little difference; the analysis results of single wheel can represent states of the wheelset. The following results are from left wheel.

The size and distribution of wear work in contact patch are showed in Fig.7 for 5 special times. It is not difficult to be found that when the creep force is large in wheel/rail contact patch, the wear work also appeared peak value as shown in Figure 7 (b) and Figure 7 (d). At this time, the severe wear region appeared in contact patch of wheel/rail. With the accumulation of train running distance, wheel tread will appear uneven wear resulting in wheel out-of-roundness. At the same time, the periodic law of wheel tread wear is affected by the coupling of the periodic change of the lateral displacement and the wheel/rail force. This is the root cause of complex multistage wear of wheel tread.

(a) Wear work distribution in 0.2s

(b) Wear work distribution in 0.5s
The vibration is accompanied with the movements of wheel/rail. The more accurate analysis results can be achieved for contact dynamic model considering wheel/rail vibration. The maximum value of vertical force is 115751.8N and the minimum value is 688.4N, which are 193.8 times and 0.012 times to wheel/rail static loading respectively. The maximum vibration amplitude of the wheel attack angle is 1.568 mrad. The lateral displacement of wheelset is approximately periodic with 0.95s and the amplitude is 3.3 mm. The longitudinal creep force and the contact patch area of wheel/rail are obviously influenced by normal force of the wheel/rail. And the wheel-rail lateral has a large impact on the lateral creep force of wheel/rail. Attack angle of wheelset has a little influence on the longitudinal and lateral creep force of wheel/rail.

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