Coupling Dynamic Simulation Between Current Shoe and Conductor Rail for Microscope

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Abstract
For the development of current shoe and conductor rail system with 120 km/h speed and above, the system theory development and the relevant engineering simulation tools for the dynamic interaction between the current shoe and conductor rail is urgent need. The dynamic analytical and simulation models of the shoe and the rail have been established under the actual working conditions. Using this dynamic simulation model, this paper has studied the dynamic characteristics of the current shoe and conductor rail system under different conditions, which gives the reference for the optimization scheme of the 120km/h current shoe and conductor rail system.

Key words: Urban Rail Transit; Current Shoe; Conductor Rail; Dynamic; Contact Force

1. Introduction
The current shoe and conductor rail system are one of the oldest electric train traction power supply modes. In 1890, the first conductor railway built in London. Comparing with the catenary flow, conductor railway has the lowest electromagnetic interference strength, good electrical conductivity, simple and convenient installation and adjustment, low cost, strong ability to combat bad weather and other advantages. So far, the current shoes and conductor rail system is still widely used in the field of urban rail transit. The world's highest operating speed is up to 174 km/h. With the rapid development of urban rail transit, the running speed of electrified trains is bound to improve in order to shorten passenger transport time. The increase of running speed will inevitably bring some influence to the dynamic performance of sliding coupling between current shoes and conductor rails. Contact force as one of the most important parameters for contact rail and shoe in microscope should be valued.

Domestic scholars have done some studies on dynamic simulation of current shoes and conductor rails. By establishing the motion model of the conductor rail and the current shoe system and analyzing the characteristics of the contact interface, Zhenyun Wang found that the contact pressure of the sliding shoes is closely related to the bending degree of the conductor rail surface [1]. The relationship among surface roughness, contact stiffness, and contact force of current shoes were studied by using fractal theory. The rigid and flexible coupling model of the current shoe and the conductor rail was established. The dynamic simulation of the shoe-rail was carried out by using the swing arm of the current shoes as the flexible body while other structures were rigid bodies. Wei Li studied the influence of train running speed and three-track installation accuracy on the relationship between shoes and rails through the dynamics. Wenjiao Wang established the simulation model of current shoes and conductor rails and the results show that it can improve the follower of the sliding shoes by changing the correlation stiffness of the current shoe system, increasing the damping, and changing the shape and slope of the elbow at the end of the conductor rail [2]. Foreign scholars mainly explored the dynamic characteristics through experiments and simulations. Weston et al. studied the steady-state and dynamic contact between current shoes and conductor rail and found the main factors affected by the vibration of the current shoes [3]. RSSB studied the dynamic response of the current shoes when sliding across the conductor rail slant and compared the vibration of the current shoes affected by different slope slopes [4].

To sum up, there are two ways to obtain the dynamic performance of shoe-rail coupling, which are online measurement and simulation, respectively. The simulation can quickly predict the coupling dynamic performance of shoe and rail under various working conditions and provide an auxiliary decision for the design of shoe-rail structure, system operation, and maintenance. Based on this, simulation of shoe-rail is used to study the dynamic performance. In order to further study the coupling dynamic mechanism of current shoes and conductor rails, starting with the actual situation and corresponding technical data of the existing conductor rail system in Guangzhou urban rail transit, the coupling kinetic equations of current shoes and conductor rails are deduced and
the dynamic simulation models of conductor rails and current shoes are established in this paper. The dynamic response of shoe-rail under different working conditions are analyzed. This study provides a reference for the design of current shoes and conductor rail collector system with 120 km/h running speed.

2. The Dynamic Model of Current Shoe

The function of the current shoes is to install on the side of the electrified train bogie and connect to the conductor rail, which provides the electrical equipment for the power supply of the electrified train. This study takes a certain type of current shoes used by Guangzhou Metro, which are mainly composed of pre-pulling springs, bearings, insulated connecting plates, brake rods, skateboard brackets, skateboards, and other parts. The spring force is transmitted by the bearing to provide contact force to the skateboard. The kinematic principle of the current shoe is similar to the lever principle. The bearing is the pivot to achieve balance through the cantilever for the spring force and contact force. The dynamic model is established according to the kinematic principle of the current shoe, as shown in Figure 1.

![Fig 1. Dynamic model of current shoe.](image)

Through above analysis, the dynamic equation and dynamic simulation model of conductor rails and current shoes are established in this paper. The dynamic response of shoe-rail under different working conditions are analyzed. This study provides a reference for the design of current shoes and conductor rail collector system with 120 km/h running speed.

\[
M_h \ddot{X}_h + C_h \dot{X}_h + K_h X_h = G_h + T_h + F_{ch} \tag{1}
\]

where \(M_h\), \(C_h\), and \(K_h\) are the mass, damping, and stiffness matrices of the current shoes, respectively. \(X_h\) is the node displacement matrix of the current shoes. \(G_h\) is the node gravity matrix of the current shoes. \(T_h\) is the pre-tensile matrix of the current shoe spring. \(F_{ch}\) is the contact force matrix of the current shoes.

3. Dynamic Model of the Conductor Rail

The conductor rail, lying on the ground, is along the shape rail layout of the track to provide the power supply for the current shoe. Taking the lower conductor rail used by Guangzhou Metro as an example, the steel aluminum composite rail surface uses a layer of stainless steel as the conductive contact surface. The base uses aluminum alloy material to supply the power. In the establishment of the conductor rail dynamics model, the stainless steel body and the aluminum alloy body are regarded as a whole as the beam element. The conductor rail is fixed by positioning line clamp and insulating bracket at a certain distance, where the positioning line clamp and the insulating bracket are equivalent to a high stiffness spring unit. The beam joints of the conductor rail body are constrained except the transition freedom in the vertical line direction (axis z-direction) and the rotational degree in the vertical line direction (axis y-direction). The current shoes enter the conductor rail through the end elbow of the conductor rail. The slope of the elbow at the end of the conductor rail is very small. The end elbow is treated as a straight beam element. The conductor rail has thermal expansion and contraction. The interval force is a certain distance through the expansion joint to connect the two-segment conductor rail. The expansion joint is the structure of the smooth line activity. According to the structural characteristics of the expansion joint, it is equivalent to three section beam. The middle short beam and the auxiliary fixed beam on both sides are consolidated through the joints. The joints of the auxiliary fixed beam and the conductor rail body overlap on both sides by establishing the constraint equation so that the expansion joint can slide along the line direction on the conductor rail. Similarly, the external forces of the conductor rail have gravity, pre-tension and contact force. Through the above analysis, the dynamic analytical and simulation model of conductor rail are obtained, as shown...
in Equation (2) and Figure 2.

\[
M_g \ddot{y}_g + C_g \dot{y}_g + K_g y_g = G_g + F_{cg} \tag{2}
\]

where \(M_g, C_g,\) and \(K_g\) are the mass, damping and stiffness matrices of conductor rails. \(y_g\) is the node displacement matrix of conductor rails (including the coupling of freedom of nodes). \(G_g\) is the node gravity matrix of conductor rail. \(F_{cg}\) is the contact force matrix of conductor rail.

4. Coupling Contact Model of the Current Shoe and Conductor Rail

The coupling contact model of skateboard and conductor rail adopts penalty function method. Considering the small elastic deformation of skateboard which makes contact between the two ends of the skateboard and the beam element of the conductor rail, the contact force of the shoe-rail is divided into two parts. As shown in Figure 3, the nodes are \(m_1\) and \(m_2\). The vertical direction displacement of the conductor rail beam element \(i-j\) and the \(m_1\) of the node is \(\Delta \kappa_i\). Assuming that the displacement of the node \(m_1\) above the unit \(i-j\) is positive, the contact is in penetration state at this time. Whereas the node \(\Delta \kappa_i\) the displacement under the unit \(m_1\) is negative \(i-j\), as shown in Figure 3.

According to the symbol of each time step \(\Delta \kappa\), the contact state of the current shoe and conductor rail is judged. Then according to the contact stiffness and the product of the \(\Delta \kappa\) as the contact force of the conductor rail and the skateboard, respectively, it can recalculate the node displacement as the next time contact net and the external load of the pantograph. So repeated, it can calculate the bow net interaction. A numerical formula for calculating the contact force is shown in Equation (3). The contact force of the current shoe and the conductor rail are in the opposite direction with equal values.

The equivalent force of the beam element nodes in different positions is different. Assuming that the contact force of the node \(m_i\) acts at the coordinate \((x,0)\) of a space beam unit, which is equivalent to two nodes by Equation (4), where the \(f_{ci}\) is the amplitude of the contact force and \(l\) is the unit length. By means of Equation (4), the contact force of a single beam element is obtained. The contact force acting on the unit is converted and assembled. The contact force matrix of the whole node coordinates is obtained. And the value of the contact force in the matrix and the position in the matrix are time-varying.

\[
f_{ci}(t) = \begin{cases} k_i \Delta \kappa_i(t), & \text{if } \Delta \kappa_i(t) \geq 0 \\ 0, & \text{if } \Delta \kappa_i(t) < 0 \end{cases} \tag{3}
\]

\[
F_{cg} = \begin{bmatrix} f_{ci}(l-x)^2(l+2x) & 0 & 0 & 0 \\ 0 & f_{ci}(l-x)^2(l+2x) & 0 & 0 \\ 0 & 0 & f_{ci}(l-x)^2 & 0 \\ 0 & 0 & 0 & f_{ci}(l-x)^2 \end{bmatrix}, \text{ for } i = 1, 2
\tag{4}
\]

Through the power Equation (1), the conductor rail dynamic Equation (2), the contact force numerical
calculation Equation (3) as well as the contact force distribution equation (4), the contact force matrix is assembled. To integrate the combined shoe rail coupling kinetic equations using Newmark-β and solve iteratively, it can obtain the displacement and contact force of the shoe rail joints so as to realize the dynamic performance evaluation of shoes and rails.

5. Validation of the Shoe-Rail Model

The deflection equation and deflection coefficient of beam with 5 spans under uniform load is:

\[ W = k \frac{ql^4}{100EI} \quad (5) \]

where \( k \) is the coefficient; \( q \) is the uniform load (N/m); \( l \) is the span length (m); \( E \) is the elastic modulus (Pa); \( I \) is the inertial moment (m\(^4\)). \( k \) along five spans from left to right are 0.644, 0.151, 0.315, 0.151, and 0.644, respectively.

The parameters of the conductor rail refer to the standard CJT 414-2012 [13] in the flow 3000 A conductor rail. The conductor rail weight in unit length is 15 kg/m. The Young’s modulus is \( 8.6 \times 10^{10} \) Pa, and the inertial moment is \( 6.4 \times 10^4 \) m\(^4\). The nominal span is 5 m tentatively. The above parameters are taken into the Equation (5) to obtain each deflection in the span, as shown in table 1.

With the same parameters, the simulation model of five-span conductor rail is established, which is only affected by gravity. The displacement in each span is obtained, as shown in table 1. Theoretical and simulation value are very close, which shows that the conductor rail simulation model is reasonable.

Table 1. Each span deflection of five-span continuous conductor rail

<table>
<thead>
<tr>
<th>Deflection (mm)</th>
<th>Calculation method</th>
<th>One-span</th>
<th>Two-span</th>
<th>Three-span</th>
<th>Four-span</th>
<th>Five-span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td></td>
<td>1.09</td>
<td>0.25</td>
<td>0.53</td>
<td>0.25</td>
<td>1.09</td>
</tr>
<tr>
<td>Simulation</td>
<td></td>
<td>1.08</td>
<td>0.26</td>
<td>0.54</td>
<td>0.26</td>
<td>1.08</td>
</tr>
</tbody>
</table>

6. The Coupling Dynamic Characteristic of the Shoe-Rail at Different Condition

There are many factors affect the dynamic flow of shoe-rail. In this paper, the influence of the key parameters, such as train running speed, conductor rail span, and end elbow slope and positioning point stiffness, on the dynamic performance of shoe-rail is analyzed. Similar to the wheel-rail, the higher the running speed, the more intense the vibration of the shoe-rail is. The conductor rail span is the key parameter of the conductor rail scheme design, which is closely related to the installation workload and economic cost. The converter enters the end elbow of the conductor rail in high speed, which will produce a large impact. The slope of elbow at the end of the conductor rail is closely related to the impact force. Reducing the stiffness of the conductor rail positioning point can increase the flexibility of the conductor rail and affect the dynamic performance of the shoe-rail.

The cross-sectional area of the conductor rail in simulation is 4400mm\(^2\). The unit length weight is 15 kg/m. The Young’s modulus is \( 86387 \) N/mm\(^2\). The nominal span is 5 m. The two sections adopt the end elbow. And the slope of the end elbow is 1.60. The equivalent stiffness of the insulating bracket is 500000 N/m. The length of the anchor section is 78.4 m. And the conductor rail is only the geometric shape of the self-weight as shown in Figure 4.

The contact stiffness of the current shoes and the conductor rail is selected as 50000 N/m in the standard EN50318. Laboratory measured a certain type of current shoes used by Guangzhou Metro. Its dynamic parameters are as follows: the skateboard mass is 2.4 kg; the swing arm mass is 2kg; the equivalent stiffness of the current shoe tensile spring is 11200 N/m; the equivalent damping is 1000 Ns/m, and the static contact force is 130 N.

6.1. Speed

The contact force is one of the key parameters to characterize the dynamic performance of shoes and rails. Under the same structural parameters, the contact force curves at different operating speeds are shown in Figure 5. It is found that, with the increase of running speed, the contact force fluctuation of the current shoes entering the conductor rail increases obviously.

The acceleration of the vertical conductor rail surface of the skateboard is another key parameter to characterize the dynamic performance of the shoe-rail. The skateboard acceleration curves are measured at different operating speeds, as shown in Figure 6. It is found that with the increase of running speed, the acceleration of skateboard is increased as the current shoes enter the conductor rail, and the variation law is
consistent with the contact force.

Statistic contact force and the numerical characteristics of the skateboard acceleration are shown in table 2. It is found that with the increase of running speed, the standard deviation of contact force becomes larger. The maximum contact force and the acceleration of skateboard increase as well.

When the current shoe enters the conductor rail at the speed of 120km/h, it has a great impact on the conductor rail. The contact force fluctuates violently with the minimum value 0 showing up. And the contact of the shoe-rail is poor. The results show that the key focus in the dynamic relationship of shoes is the process of entering the contact cycle by current shoes.

<table>
<thead>
<tr>
<th>Velocity (km/h)</th>
<th>Contact force (N)</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>125.89</td>
<td>19.6</td>
<td>0</td>
<td>204.91</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>125.83</td>
<td>23.4</td>
<td>0</td>
<td>270.52</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>125.59</td>
<td>29.3</td>
<td>0</td>
<td>331.50</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>125.31</td>
<td>36.6</td>
<td>0</td>
<td>389.18</td>
<td></td>
</tr>
</tbody>
</table>

When the current shoes run into the conductor rail, the actual conductor rail line is relatively longer in the line interval section of the generally straight section. Expansion joints are installed in the conductor rail interval in the straight section to study of the expansion joints on the dynamic performance of the shoe-rail effect.

The length of the expansion joint is 1875 mm. The expansion joint is located at 3 m span and the interval of two expansion joints is 50 m.

Different operating speeds, through the contact force curve containing the expansion joint section, are collected, as shown in Figure 7. It is found that the contact force of the current shoes through the expansion joint increases with the increase of running speed. Comparing the contact force curves of the end elbow and the
expansion joint, it is found that the vibration of the end elbow is much more intense. The end elbow is the key area restricting the dynamic performance of the shoe-rail.

The numerical characteristics of the statistical contact force, as shown in Table 3, show that the standard deviation (SD) of the contact force becomes larger with the increase of the running speed. When the current shoe passes through the expansion joint at 120km/h, it has a great impact on the conductor rail and causes poor contact quality of the shoe-rail. The research shows that the emphasis area in the dynamic relationship of shoes-rails should be laid on the process, by which the current shoes pass through the expansion joints.

The dynamic performance of shoes and rails with different running speeds through the expansion joint section satisfies the standard requirements, which shows that the shoe-rail relationship of straight section satisfies the running speed requirement of 160 km/h in theory.

![Figure 7. Contact force curves at different speeds through sections with expansion joints.](image)

**Table 3.** Digital characteristics of contact forces at different speeds through sections with expansion joints.

<table>
<thead>
<tr>
<th>Velocity (km/h)</th>
<th>Mean (N)</th>
<th>SD(N)</th>
<th>Min(N)</th>
<th>Max(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>118.31</td>
<td>5.39</td>
<td>82.23</td>
<td>140.61</td>
</tr>
<tr>
<td>100</td>
<td>118.42</td>
<td>6.66</td>
<td>89.54</td>
<td>149.21</td>
</tr>
<tr>
<td>120</td>
<td>118.39</td>
<td>7.89</td>
<td>88.94</td>
<td>147.33</td>
</tr>
<tr>
<td>140</td>
<td>118.40</td>
<td>9.29</td>
<td>85.96</td>
<td>150.46</td>
</tr>
<tr>
<td>160</td>
<td>118.40</td>
<td>9.63</td>
<td>85.26</td>
<td>149.53</td>
</tr>
</tbody>
</table>

6.2. Span

The influence of the span on the dynamic performance of shoe-rail is studied. The span of the conductor rail refers to the distance between the two suspension points, which is generally 5, 4, and 3 m. The simulation model is established based on those three spans. Because the end elbow has a great influence on the dynamic performance of the shoe-rail, all the following conductor rail models contain the end elbow. While the expansion joint has less influence, the expansion joint structure is not considered. Figure 8 gives the contact forces of those three spans. Compared to those contact forces, the contact force of 3 m span reaches to a stable value in the 10 m conductor rail length. However, the length is 12.5 and 20 m for 4 and 5 m span, respectively. Due to the conductor rail relaxation, the smaller the span, the relaxation of conductor rail in the gravity direction is smaller. The smoother the conductor rail which makes converter to enter a stable state easier. The contact force of 3 and 4 m enters a stable state early after the current shoe enters the conductor rail. The contact force with a span of 4 m fluctuates greatly in the middle section.
In the end elbow area, the contact force fluctuates greatly. In order to find out shoe-rail relationship at different span, the contact force in middle section 20~70 m is compared, as shown in table 4. The results showed that the contact force of 4 m span is larger than 3 and 5 m span, as well as the range between maximum and minimum contact force. The research shows that it is not appropriate to use 4m span in conductor rail. Considering the economy, 5 m span is an acceptable choice.

Table 4. Digital characteristics of contact forces between different spans.

<table>
<thead>
<tr>
<th>Span (m)</th>
<th>Mean (N)</th>
<th>SD (N)</th>
<th>Min (N)</th>
<th>Max (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>129.15</td>
<td>12.11</td>
<td>100.43</td>
<td>162.63</td>
</tr>
<tr>
<td>4</td>
<td>129.12</td>
<td>27.08</td>
<td>56.25</td>
<td>199.37</td>
</tr>
<tr>
<td>5</td>
<td>129.29</td>
<td>11.28</td>
<td>101.52</td>
<td>160.72</td>
</tr>
</tbody>
</table>

6.3. End elbow slopes

When the current shoes enter the end elbow, the contact force fluctuates greatly. The influence of the end elbow structure on the dynamic performance of the shoe-rail is studied. The end elbow slope is an important parameter of the end elbow structure design. The following simulation studies the dynamic performance of shoes and rails of 1:50, 1:60, and 1:70 slope values.

Table 5 compared the numerical characteristics of the skateboard acceleration of the conductor rail at 0~20m and 60~80m when the current shoes enter and leave the slope of different end bends. The minimum contact force of 1:60 for the entry and departure of the converter is larger and the maximum value is small, indicating that the vibration of the shoe rail with a slope of 1:60 is smaller.

Table 5. Digital characteristics of panhead acceleration for different end elbow slopes.

<table>
<thead>
<tr>
<th>Point (m)</th>
<th>Slope</th>
<th>Min (m/s²)</th>
<th>Max (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~20</td>
<td>1:50</td>
<td>-105.22</td>
<td>62.83</td>
</tr>
<tr>
<td>0~20</td>
<td>1:60</td>
<td>-94.63</td>
<td>58.74</td>
</tr>
<tr>
<td>0~20</td>
<td>1:70</td>
<td>-104.48</td>
<td>81.99</td>
</tr>
<tr>
<td>60~80</td>
<td>1:50</td>
<td>-271.21</td>
<td>67.86</td>
</tr>
<tr>
<td>60~80</td>
<td>1:60</td>
<td>-228.29</td>
<td>50.90</td>
</tr>
<tr>
<td>60~80</td>
<td>1:70</td>
<td>-228.90</td>
<td>53.33</td>
</tr>
</tbody>
</table>

In order to reduce the impact of current shoes on the rail when entering the conductor rail, it is advisable to use an end elbow with a slope of 1:60.

6.4 Stiffness at specified points

The conductor rail is installed on the insulating bracket. If the elastic element is added to the insulating bracket, the influence of the stiffness change of the positioning point on the dynamic performance of the shoe track is studied.
When the current shoe pass through the conductor rail at 120 km/h, the simulation results of the shoe-rail contact force and the current shoe acceleration and displacement at 50000 N/m stiffness point are given in Figure 9.

![Figure 9. Dynamic performance parameters with the stiffness of 50000 N/m.](image)

The contact force of the conductor rail are measured at 0~20m and 60~80m with different positioning point stiffness, as shown in table 6. The contact force standard deviation reaches the smallest when the positioning point stiffness is 50000 N/m. The results show that increasing the elasticity of the positioning point can improve the contact force of the current shoes when they enter the conductor rail. But it has little effect on the contact force of the current shoes when leaving the conductor rail.

<table>
<thead>
<tr>
<th>Points (m)</th>
<th>Stiffness(N/m)</th>
<th>Mean (N)</th>
<th>SD (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~20</td>
<td>500000</td>
<td>127.08</td>
<td>66.19</td>
</tr>
<tr>
<td>0~20</td>
<td>100000</td>
<td>126.83</td>
<td>61.00</td>
</tr>
<tr>
<td>0~20</td>
<td>50000</td>
<td>126.48</td>
<td>60.67</td>
</tr>
<tr>
<td>60~80</td>
<td>500000</td>
<td>118.79</td>
<td>18.74</td>
</tr>
<tr>
<td>60~80</td>
<td>100000</td>
<td>118.51</td>
<td>18.92</td>
</tr>
<tr>
<td>60~80</td>
<td>50000</td>
<td>118.65</td>
<td>18.64</td>
</tr>
</tbody>
</table>

7. Conclusions

1. Based on the structural characteristics analysis and dynamic equations of current shoes and conductor rail, the dynamic simulation model of the current shoe and conductor rail were established.
2. Through the simulation of shoe-rail, it is found that, with the increase of running speed, the contact force of shoes and rails in the middle section of the end elbow and the expansion joint increases. The end elbow area, where the current shoes enter the conductor rail, is the area with poor dynamic performance of the shoe-rail.
3. The results show that the dynamic performance of the shoe-rail with the straight section of the expansion joint can satisfy the running speed requirement of 160 km/h in theory.

By comparing the dynamic response of the shoe-rail with different conductor rail parameters, the nominal span of the conductor rail at 120 km/h speed should be 5 m and the slope of the end elbow should take 1:60. Besides, the stiffness of the positioning point should be 50000 N/m. The conclusion of the study is to provide a reference for adapting to the 120 km/h shoe-rail system scheme.

References