Study on Key Factors on Ride Comfort of Low-floor Light Rail Transit

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Abstract. In order to meet the public’s demand for higher and higher comfort level of low-floor trams, this paper analyzes the influence on comfort level from four aspects: equivalent conicity, hinge arrangement position, suspension parameters and track geometry quality. The results show that track geometry quality plays a decisive role in influencing the comfort of low-floor trams, and the power spectral density of track irregularity has a greater impact on the comfort of vehicles than the standard deviation and peak value. Finally, it is suggested that main line maintenance should be shifted from the current management of standard deviation and peak value to track power spectral density curve management. At the same time, it is suggested that vehicle manufacturer should study the track geometry quality more deeply.

1. Introduction
As a very important means of urban rail transit, modern low-floor tram has the advantages of more cost-saving, energy-saving and environmental protection, convenient ride and strong sense of science and technology because of its flexible marshalling, small turning radius, low floor surface, sharing right of way with social vehicles, fashionable appearance and so on. It is favored by many urban managers and the public in the world.[1-3]

With the development and progress of society, the public's requirements for the comfort of trams are getting higher and higher. Whether it is an empty and heavy vehicle or a new wheel wear wheel, the comfort of the vehicle is required to reach the comfort level, that is, Nmv<2.5 (comfort index). This is a huge challenge for the small low-floor tram.[4-8]

2. Methods
To analyze the causes of the problems, this paper carried out relevant research work on improving comfort from four aspects: equivalent taper of tread, hinged arrangement position, suspension parameters and track irregularity.

This paper is based on the correlation analysis of 6 modules 70 % low floor light rail transit. Each group of vehicles consists of two 3-module units, and each unit is connected by a permanent coupler and a throughway. Each unit consists of two powered vehicle modules and an unpowered vehicle module. Mc module and Tp1 module or Msc module and Tp2 module are connected by fixed hinge, elastic hinge and through channel. The M1 module and the Tp1 module or the M2 module and the Tp2 module are connected by fixed hinges, free hinges and through-paths. The Mc, M1, M2 and Msc modules are equipped with power bogies with the same structure; the Tp1 and Tp2 modules are equipped with the same structure of unpowered bogies. The vehicle parameters are shown in Table 1, and the vehicle formation is shown in Figure 1.

<table>
<thead>
<tr>
<th>Table 1. Vehicle parameters</th>
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<tbody>
<tr>
<td>Parameter point</td>
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<tr>
<td>Train formation</td>
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<tr>
<td>Maximum test speed</td>
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<tr>
<td>Maximum operation speed</td>
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<tr>
<td>Train size</td>
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<tr>
<td>Measure distance</td>
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<tr>
<td>Unladen weight</td>
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<tr>
<td>Maximum axle load</td>
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<tr>
<td>Power bogie form</td>
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<td>Unpowered bogie form</td>
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</table>

3. Analysis
3.1. Influence of equivalent conicity
The equivalent conicity of tread directly affects the stability of vehicle motion. If the vehicle motion stability...
is insufficient, it will seriously affect the comfort. Therefore, first of all, it is necessary to analyze whether the equivalent conicity of the vehicle tread is reasonable, that is, whether the stability is satisfied.

The new wheel tread with equivalent conicity of 0.08 and the wear wheel tread with equivalent conicity of 0.35 are used as input to analyze the stability of vehicle motion. From the analysis of Fig. 2, we can see that the train is driven on a straight line, and a 5mm sine wave transverse track excitation is applied within the initial 200 m length to observe the subsequent wheelset lateral displacement. It can be seen from the time domain integral hunting bifurcation diagram 2 that the critical speed of the new wheel is 220 km/h, and the critical speed of the wear wheel is 150 km / h, which meets the requirement of the maximum running speed of 80 km/h. The critical speed of the wear wheel has a margin of 50 %. Therefore, whether it is a new wheel or a worn wheel, the equivalent conicity of the tread has no decisive influence on the comfort of the vehicle within the range of 80 km/h.

3.2. Influence of hinge position

The position of the hinge device between Msc and Tp1 (fixed hinge and elastic hinge combination) is aligned with the hinge device between Tp1 and M1 (fixed hinge and free hinge combination). By comparing the comfort changes before and after the hinge replacement (Figure 3), it can be seen that there is no significant improvement in the comfort of Msc and Tp1 vehicles except for the obvious changes in the comfort of M1 vehicles.

3.3. Influence of suspension parameters

When the vertical stiffness of the secondary system is constant, the influence of different horizontal stiffness of the secondary system on the degree of comfort is analyzed. It can be seen from Table 2 and Figure 4 that the comfort of all vehicle modules decreases with the decrease of the horizontal stiffness of the secondary system, whether it is in the state of the new wheel or the wear wheel of the vehicle. However, even if the horizontal stiffness of the secondary system is reduced by 80 %, it cannot meet the requirements of comfort, and too small stiffness cannot be achieved in engineering. It can be seen that the vehicle comfort cannot be significantly improved by reducing the horizontal stiffness of the secondary system.

Table 2. Secondary horizontal stiffness with different proportional coefficients

<table>
<thead>
<tr>
<th>Proportional coefficient</th>
<th>0.2</th>
<th>0.3</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
<th>1</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Msc (MN/m)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.14</td>
</tr>
<tr>
<td>Car M1 (MN/m)</td>
<td>3.0</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
<td>1.0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Car Tp1 (MN/m)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Fig. 3. Hinge position

Fig. 4. The influence of the change of the horizontal stiffness of the secondary system on the comfort degree

When the horizontal stiffness of the secondary system is constant, the influence of different vertical
stiffness of the secondary system on the degree of comfort is analyzed. It can be seen from Table 3 and Figure 5 that when the horizontal stiffness is constant, the comfort of all vehicles decreases with the decrease of the secondary vertical stiffness. The secondary vertical stiffness of Msc and Tp1 in the new wheel state when the proportional coefficient is not greater than 1 can make the vehicle comfort meet the requirements of $N_{mv}<2.5$, but in the wear wheel state, even a small secondary vertical stiffness cannot achieve $N_{mv}<2.5$. The M1 car with shorter module length and lighter empty car weight cannot meet the requirements of $N_{mv}<2.5$ whether in the new wheel or the wear wheel. It can be seen that by reducing the vertical stiffness of the secondary system, the problem of high comfort of the M1 module in the new wheel wear wheel and the vehicle module in the wear wheel state cannot be solved.

Table 3. Secondary vertical stiffness with different proportional coefficients

<table>
<thead>
<tr>
<th>Proportion al coefficient</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
<th>1</th>
<th>1.1</th>
<th>1.3</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Msc (M1) (MN/m)</td>
<td>0.16</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Tp1 (MN/m)</td>
<td>0.27</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Fig. 5. The influence of the change of the vertical stiffness of the secondary system on the comfort degree

3.4. Influence of track irregularity

The track irregularity affects the movement of the wheelset through the wheel-rail dynamic interaction force, which causes the vibration of the vehicle system. Track irregularity has a significant impact on vehicle dynamic response, and there is no uniform and perfect standard for track irregularity used in the field of vehicle dynamics simulation, which brings many problems to the vehicle dynamics simulation of new vehicles [9-11].

In this paper, two kinds of track irregularity BG_US5_QN2 and BG_GEM_QN2 are used to analyze and calculate the vehicle comfort. Firstly, the two kinds of track irregularity are compared and analyzed in the cut-off wavelength range of 3–25m specified by UIC518. From Figure 6, it can be seen that the time domain amplitude, peak value and standard deviation of the two track irregularities of BG_US5_QN2 and BG_GEM_QN2 are basically the same, but the power spectral density is quite different.

Fig. 6. Comparison of track irregularity

(a) Comparison of track irregularity curves

(b) Comparison of standard deviation

(c) Comparison of extreme value

(d) Comparison of power spectral density curves

Fig. 7. GB_US5_QN2 track irregularity

Fig. 8. BG_GEM_QN2 track irregularity
Based on the analysis of vehicle comfort based on BG_US5_QN2 and BG_GEM_QN2 two kinds of track irregularity, it is found that when using BG_US5_QN2 track irregularity calculation, the comfort Nmv of the new wheel state of the vehicle is more than 2.5 after the speed exceeds 70 km/h, and the comfort Nmv of the wear wheel state of the vehicle exceeds 2.5 when the speed does not reach 70 km/h, as shown in Figure 7; when using BG_GEM_QN2 track irregularity calculation, there is no sign of exceeding the standard in the speed range of 120 km/h, whether the vehicle is a new wheel or a wear wheel, as shown in Figure 8. It can be seen that the influence of different track irregularity on vehicle comfort is very large.

4. Conclusion and recommendations

From the perspective of the influence of tread equivalent conicity, hinged arrangement position, suspension parameters and track irregularity on vehicle comfort, the equivalent conicity has no effect on comfort within the specified test speed range. The change of hinge position does not improve the comfort of Msc and Tp1 vehicles, and the improvement of comfort of M1 is also very limited. No matter how small the vertical and horizontal stiffness of the secondary system is reduced, the comfort cannot be improved; track irregularity plays a decisive role in improving comfort. Even if the standard deviation and peak value of different track irregularity are the same, if the power spectral density is different, the vehicle comfort is also very different. It can be said that the amplitude of the power spectral density of the track irregularity determines the vehicle comfort.

At present, the research on the evolution law of track irregularity at home and abroad is mainly carried out in the time domain, focusing on the evolution law of irregularity amplitude and standard deviation with operating mileage or time, so the track maintenance management is managed according to standard deviation or peak value. Because the time domain analysis can not know the variation of the wavelength components of the track irregularity, the influence of the wavelength components on the track irregularity is ignored. It is suggested that in the future track maintenance, the track power spectral density should be the main factor, supplemented by standard deviation and peak value, and the track should be maintained and managed in sections, so that the dynamic performance of the vehicle, especially the comfort index, can be guaranteed.

The quality of track irregularity determines the calculation results of dynamics. Previously, vehicle OEMs usually optimized vehicle parameters to achieve vehicle comfort index requirements. Now, in addition to studying the optimization of the parameters of the vehicle itself, we should also study the influence of the line conditions on the vehicle, and put forward reasonable suggestions for the line design and construction units.

References