Numerical and experimental investigation on motion stability of a 200km/h passenger electric locomotive

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Abstract

A new type of 200km/h passenger electric locomotive is designed to satisfy the demand of the speed-raising on existing railways. Aiming at the motion stability of the locomotive, both the simulation and the roller rig tests are conducted. Based on the theory of the vehicle-track coupled dynamics, the effect of the main suspension parameters on the motion stability is analyzed for optimization with the consideration of the ride comfort. The simulated results show that the nonlinear critical speed of the original locomotive is 234km/h, which does not satisfy the operation requirement. By increasing the stiffness of the secondary suspension, the motion stability of the locomotive can be improved obviously. The longitudinal and lateral stiffness of secondary suspension are suggested to 0.42MN/m, and the vertical stiffness is suggested to 0.8MN/m. After optimization, the nonlinear critical speed of the locomotive increases to 292km/h, and the increase of the ride comfort index is not obvious. Experimental tests are carried out on the roller rig to validate the optimization. On the roller rig tests, when the speed increases to 280km/h, the wheelset vibration attenuates to equilibrium position quickly, which indicates the locomotive is still stable at this speed. The tested results also demonstrate that the ride comfort index of the locomotive satisfies the standard at the speed of 200km/h.

Keywords: 200km/h locomotive, motion stability, ride comfort, stiffness of secondary suspension, roller rig test.

1. Introduction

After the sixth railway speed boost, the velocity of the passenger train on the speed-raised line has risen to 200km/h or above, which will obviously increase the passenger handling capacity of the railway system. To satisfy the demand of the speed-raising on existing railway, a new type of 200km/h passenger electric locomotive is designed. At the design process, the dynamic performance of the whole vehicle is very important, especially for the motion stability. The higher motion stability of the locomotive is needed to meet the demand of the speed of 200km/h. The dynamic parameters have a significant effect on the motion stability of the locomotive, so it is critical to optimize the suspension parameters at the beginning of the design process [1].

A number of scholars focused on the motion stability of the locomotive, and many methods have been proposed to calculate and improve the nonlinear critical speed. True [2] discussed the nonlinear dynamics and its application to vehicle systems dynamics problems, many equilibrium states are defined and related to the multiple systems. Aiming at the calculation methods of the motion stability, Polach [3, 4] compared the linearized and nonlinear methods used in railway vehicle, and different methods were introduced from the view of industrial applications. The influence of suspension and structure parameters on the motion stability of the locomotive was detailed introduced in [5, 6], it is very important to matching the parameters for motion stability and running comfort. The vehicle system consists of many coupled components, the dynamic behavior of the vehicle should be overall considered in the optimization process [7, 8].

For the new type of locomotive, this paper investigates the effect of the main suspension parameters on the motion stability, based on the theory of the vehicle-track coupled dynamics. [9] The optimized parameters are proposed in consideration of the nonlinear critical speed and the ride comfort. On the roller rig test, the motion stability and the ride comfort of the locomotive are main tested, and the results not only validate the optimization, but also give an evaluation of the dynamic behavior of the locomotive.

2. Coupled dynamic model

One eight-axle locomotive consists of two locomotives of 2B0 type. To decrease the wheelset dynamic interaction, the motors is mounted on the bogie, which will reduce the unsprung mass significantly. According to the actual structure,
the coupled dynamic model of the locomotive is established based on the theory of the vehicle-track coupling dynamics, as shown in Fig. 1. The coupled dynamic model is widely used by researchers and railway organizations around the world to investigate the dynamic behavior of railway train and track [10-13]. The main parameters of the locomotive model are listed in Table 1.

### Table 1. Main parameters of the locomotive model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axle load</td>
<td>18000</td>
<td>kg</td>
</tr>
<tr>
<td>Bogie distance</td>
<td>9500</td>
<td>mm</td>
</tr>
<tr>
<td>Wheel base</td>
<td>2,800</td>
<td>mm</td>
</tr>
<tr>
<td>Wheelset radius</td>
<td>525</td>
<td>mm</td>
</tr>
<tr>
<td>Primary suspension stiffness (x/y/z)</td>
<td>21.65/3.75/1.1</td>
<td>MN/m</td>
</tr>
<tr>
<td>Primary damper z-axis</td>
<td>50</td>
<td>kN·s/m</td>
</tr>
<tr>
<td>Secondary suspension stiffness (x/y/z)</td>
<td>0.294/0.294/0.6465</td>
<td>MN/m</td>
</tr>
<tr>
<td>Secondary damper y-axis (one side)</td>
<td>800</td>
<td>kN·s/m</td>
</tr>
<tr>
<td>Secondary damper z-axis (one side)</td>
<td>50</td>
<td>kN·s/m</td>
</tr>
<tr>
<td>Secondary damper z-axis (one side)</td>
<td>45</td>
<td>kN·s/m</td>
</tr>
</tbody>
</table>

3. Influence of the main suspension parameters on motion stability

3.1. Nonlinear critical speed of the locomotive

The nonlinear critical speed of the locomotive was calculated according to the method in [7] and [14]. The nonlinear critical speed of the original locomotive is shown in Fig. 2. Under the initial excitation (measured irregularity), the wheelset lateral displacement shows a stable limit cycle with decreasing the running speed, and the amplitude is about 10 mm. When the speed decreased to 250 km/h, the lateral displacement of the wheelset shows a downward trend. When the speed decreased to 234 km/h, the wheelset vibrated in a small limit cycle (amplitude<1 mm), the system can be considered stable. So, the nonlinear critical speed of the locomotive is about 234 km/h, which is not meeting the operation requirement.

3.2. Optimization of the secondary suspension parameters

The nonlinear critical speed of the locomotive with original parameters is about 234 km/h, the safety margin is not enough
for the operation speed of 200 km/h. According to the practical experience and comparative analysis, the secondary stiffness is relatively small, which may cause the lower nonlinear critical speed.

In order to improve the motion stability of the locomotive, three sets of optimized parameters of secondary stiffness are proposed, as listed in Table 2. The nonlinear critical speeds of the optimized locomotive are simulated. It can be found that when only increase the secondary stiffness, the nonlinear critical speed of the locomotive increased obviously. When the longitudinal and lateral stiffness of secondary suspension increased to 0.4 MN/m, the nonlinear critical speed increased to 290 km/h. And when the stiffness increased to 0.8 MN/m, the improvement of the motion stability is not obvious. So, the longitudinal and lateral stiffness of secondary suspension are suggested to 0.4 MN/m.

Table 2. Optimized parameters of secondary stiffness

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Longitudinal stiffness (MN/m)</th>
<th>Lateral stiffness (MN/m)</th>
<th>Vertical stiffness (MN/m)</th>
<th>Nonlinear critical speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>0.266</td>
<td>0.266</td>
<td>0.6465</td>
<td>234</td>
</tr>
<tr>
<td>Set 1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
<td>290</td>
</tr>
<tr>
<td>Set 2</td>
<td>0.6</td>
<td>0.6</td>
<td>0.8</td>
<td>302</td>
</tr>
<tr>
<td>Set 3</td>
<td>0.8</td>
<td>0.8</td>
<td>1.4</td>
<td>307</td>
</tr>
</tbody>
</table>

Table 3. Comparison of the ride comfort index

<table>
<thead>
<tr>
<th>Scheme</th>
<th>$\Delta_{\text{max}}(g) /y$</th>
<th>$\Delta_{\text{max}}(g) /z$</th>
<th>Sperling index /y</th>
<th>Sperling index /z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>0.13</td>
<td>0.07</td>
<td>2.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Optimized</td>
<td>0.14</td>
<td>0.08</td>
<td>2.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Considering the motion stability of the locomotive and the manufacturing capacity of the secondary spring, the longitudinal and lateral stiffness of secondary suspension are optimized to 0.42 MN/m, and the vertical stiffness is optimized to 0.8 MN/m in the end. After optimization, the calculated nonlinear critical speed is 292 km/h, as shown in Fig. 3. It can be seen that the attenuation of the wheelset lateral displacement is quick, and the motion stability of the locomotive is correspondingly promoted.

As known, the secondary stiffness is closely related to the ride comfort of the locomotive. Therefore, when increase the secondary stiffness to promote the motion stability, its influence on the ride comfort should be analysed. Both the ride comfort index of the original and the optimized locomotive are calculated, as shown in Table 3. The measured irregularity is used in the simulation to reflect the actual situation, and the running speed is 200 km/h.

It can be seen from Table 3 that, when the secondary stiffness increased to the optimized value, the increase of the ride comfort index is not obvious. So, it is practicable to sacrifice a little ride comfort to increase the motion stability of the locomotive.

3.3. Optimization of primary suspension parameters

It is known that the primary stiffness have a significant influence on the motion stability of the locomotive. So, the variation trend of the nonlinear critical speed with the longitudinal and lateral stiffness of the primary suspension is calculated, as shown in Fig. 4 and Fig. 5. The secondary stiffness adopted the optimized value in the simulation.

Figure 3. Nonlinear critical speed of the optimized locomotive

Figure 4. Variation trend of the nonlinear critical speed with the primary longitudinal stiffness
Figure 5. Variation trend of the nonlinear critical speed with the primary lateral stiffness

As for the primary longitudinal stiffness, the maximum nonlinear critical speed is 389 km/h when its value is about 7 MN/m. However, the tractive characteristics and the longitudinal vibration of the locomotive are seriously influenced by the longitudinal stiffness of the primary suspension.[15-17]

The required nonlinear speed can be satisfied when the longitudinal stiffness is 21.65 MN/m, so it is recommended to keep the original value.

It can be found from Fig. 5 that, in the stiffness range (<4 MN/m), the nonlinear critical speed of the locomotive is obviously increased with the increase of the primary lateral stiffness. And when the stiffness is greater than 4 MN/m, there is almost no effect on the motion stability. So, the value of primary lateral stiffness is suggested to original.

4. The roller rig test

The full-scale roller rig is very useful for both theoretical research and design verification, and the dynamic performance of the new vehicle can be tested before the railway line tests [7]. After the design process, the new type of 200 km/h passenger electric locomotive was manufactured and tested on the roller rig in Chengdu. The testing results can verify the previous analysis.

The nonlinear critical speed and the ride comfort are the main testing content for the locomotive. The testing methods are detailed introduced in [7]. The instruments of sensors employed in the testing are illustrated in Fig. 6. The displacement sensor mounted on the wheelset was used to detect the lateral displacement, and the acceleration sensor mounted on the cab seat was used to assess the ride comfort of the locomotive.

Fig. 7 gives the attenuation of the wheelset lateral displacement in speed range of 200–280 km/h. It can be found that the vibration of the wheelset quickly attenuates to equilibrium position at tested speeds, which means the system is still stable at the speed of 280 km/h. The test results demonstrated the locomotive can run at the designed speed of 200 km/h, so the higher speed test was not conducted.
Through the roller rig test, the vibration accelerations on the cab seat were determined. According to the Chinese locomotive standard TB/T 2360-93, the ride index can be calculated. The lateral and vertical ride indexes are 2.73 and 2.17, respectively, at the speed of 200 km/h. The test results indicated that the ride comfort of the locomotive satisfies the standard. The comparison of the experimental and the simulation results shows good agreement.

5. Conclusion

This article mainly investigated the motion stability of the 200 km/h passenger electric locomotive by simulation and roller rig test. Analysis results show that the nonlinear critical speed of the original locomotive is too low to satisfy the operation speed of 200 km/h. After optimization, the secondary longitudinal and lateral stiffness were suggested to 0.42 MN/m, and the secondary vertical stiffness was suggested to 0.8 MN/m. The primary suspension stiffness was suggested to original values. The ride comfort of the locomotive was not affected obviously by increasing the secondary stiffness. The tested results on roller rig also indicated that when the speed increased to 280 km/h, the locomotive is still stable. The ride comfort index at the speed of 200 km/h satisfied the standard.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References


