Study on the evolution of dynamic performance of high-speed EMU after long-term service

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Abstract. In order to find the influence of wheel and rail wear about dynamic performance of the high-speed railway vehicle in the actual operation process, a high dimensional strong nonlinear dynamic model of the high-speed vehicle is established, and measured wheel profile is used to characterize contact geometry between wheel and rail, and relationship between stiffness of steering rubber joint and dynamic performance of railway vehicle is studied in different wheel/rail wear state. Results show, With the increment of wheel and rail wear and equivalent conicity, that stability of hunting motion of vehicle decreases, stability and safety of the vehicle all deteriorate. Moreover, with the increment of longitudinal steering joint stiffness, critical speed, lateral stability and safety of vehicles increases gradually. When it goes above 17.5MN/m, with the increments of critical speed, lateral stability and safety tend to be stable. With the increment of lateral steering joint stiffness, critical speed of vehicle tends to increase first and then decrease, and finally tends to be stable around 5MN/m, which reaches the maximum when the stiffness is 2.5MN/m. Lateral stiffness of steering joint has little influence on lateral stability of the vehicle; At low equivalent conicity, vehicle running safety decreases slightly with the increment of lateral stiffness of steering joint, while equivalent conicity increases, the vehicle running safety deteriorates sharply with the increase of lateral stiffness of steering joint. In conclusion, in order to adapt to different equivalent conicity, the optional range of longitudinal stiffness of steering joint is suggested to concentrated in 5~17.5MN/m, while its lateral stiffness is suggested to be within 2~5MN/m.

1. Introduction
In recent years, China’s high-speed railway has developed rapidly. However, with a rapid increment of operating time, running speed and loading weight, wear of wheel and rail also increases quickly, and contact condition of wheel and rail deteriorates severely, and leads to more prominent problems of vehicle vibration and noise[1]. At the same time, characteristics of various suspension elements in vehicle system will also change with the increment of service time, such as primary steel spring, secondary air spring, all kinds of damper and so on, which will also have an obvious impact on the running quality of railway vehicle. Therefore, it is necessary to pay close attention to the influence of coupling change of wheel and rail wear and suspension parameters on the vehicle system.

With the increment of vehicle service time, wheel/rail friction produces severe wear, which causes deformation of wheel tread and rail profile, and result in an obvious change of wheel/rail contact geometry, and further leads to abnormal vibration of vehicles, serious wear, and even derailment
accident. At present, many scholars at home and abroad have studied influence of wheel and rail wear on vehicle running quality. Paper[2] measured shape of each wheel, and got 5 set of wheel type surface wear working conditions, and combined with selected structure parameters of vehicle and characteristics of the lines, vehicle dynamics simulation was carried out by using multi-body dynamics software, and analyzed the dynamic characteristics of vehicle under different wear conditions; Paper[3, 4] and [5] analyzed tread wear rule from a statistical perspective, and calculated effect of tread wear on wheel/rail contact geometry and equivalent conicity; Paper[6] established vibration system mathematical model of railway passenger car, which considered stiffness of anti-hunting damper and secondary lateral damper, and differential equations were got by variable transformation with railway vehicle system conveniently, as well as gets linear and nonlinear approximate calculation method of critical velocity; Paper[11] and [12] established high-speed vehicle system dynamics model and failure model of suspension parameters on new and worn wheel/rail, and wheel/rail contact geometry relationship and dynamics simulation were done, and analyzed change of vehicle dynamic performance when normal and abnormal work of suspension parameters. Paper[13] analyzed the effect of hollow wheels on wheel/rail contact geometry and vehicle stability. It was concluded that hollow wheels do not promote hunting, but could worsen lateral vibration of bogie.

In this paper, a high dimensional strong nonlinear dynamic model of high-speed railway vehicle is established, and continuous wear tread and rail profile measured in work field are used to simulate and analysis. At the same time, the effect of stiffness of steering joints on the dynamic behavior of vehicle under the wear wheel and rail is considered. The simulated results show that wheel and rail wear and stiffness of steering joints have a great effect on dynamic performance of railway vehicle, and it is necessary to optimize suspension parameters after considering wheel and rail wear.

2. Wheel profile wear and evolution of wheel-rail contact geometry
Wheel and rail wear directly determines running quality and periodic time of spinning wheel. In order to get actual wheel/rail contact state of vehicle as much as possible, worn profile LMB10 is measured at different operating mileage, and matches with measured rail 60D. The profiles of wheels in different wear mileage are shown in figure 1. Obviously, worn tread area is mainly within the range ±20mm from rolling circle and the waist of flange, and with the increment of operating mileage, worn depth and width gradually increases, with the maximum even approaching 2mm. According to the UIC519 standard, Nominal equivalent conicity refers to the conicity corresponding to amplitude of wheel set hunting motion is 3mm. Therefore, with the increment of worn tread’s depth and width, nominal equivalent conicity will also change significantly, which has a huge impact on the running quality of railway vehicle[14].
Using to measured wheel profile in operating field, and matches with rail profile measured in WuGuang line, and analysis wheel and rail interacting geometry relationship under worn wheel profile from the original tread to 390,000km after operation, as shown in figure 2 (Among them, inner distance of wheel set is 1353mm, rail gauge is 1435mm, and rail cant is 1:40). Obviously, in the initial wear stage, both wheel and rail, contact bandwidth are relatively concentrated. Contact point area of rail is concentrated in the inner side of the symmetrical surface of rail, while contact point area of wheel tread is distributed on both sides of rolling circle. With the increment of mileage in service, wheel and rail wear increases, and contact bandwidth of wheel and rail increases gradually. Among them, the rail contact zone is gradually developed to the side of track gauge angle, while the wheel tread contact zone is gradually widened to flange zone. Theory and practice indicate that, With increment of contact point bandwidth, contact stress of wheel and rail decreases gradually, which can slow down the wear between wheel and rail, and be beneficial to maintenance of wheel and rail profile.

3. Vehicle system dynamics model

Axle box steering rubber joints is an important part connecting wheel set and bogie, which bears vertical force of bogie, longitudinal force generated during traction and braking, and lateral force of wheel set generated during operation of EMU\(^{(15)}\). With the increment of service time, the rubber of axle box steering joints will produce fatigue, creep deformation, cracking and other faults, which seriously affect stiffness of axle box steering joints. In order to explore effect of stiffness of axle box steering joints on vehicle dynamics performance, in this paper, software Simpack is used to build a single motor train model, including a car body, two bogies, four wheel set and 8 axle box steering joints. Vehicle dynamics performance is simulated based on measured wheel/rail profile. Among them, car body, bogie and wheel set each have 6 degrees of freedom, and the 8 crankcases each have 1 nod degree of freedom. Each rigid body is connected by primary suspension, secondary suspension and various damper. Vehicle dynamics model is as follows\(^{(16)}\).

\[
M \ddot{X} + C \dot{X} + KX = P
\]

(1)

Where, M, C and K respectively represent mass matrix, damping matrix and stiffness matrix of railway vehicle, X represents generalized displacement of railway vehicle system, and P represents the generalized load.

4. Influence of stiffness of axle box steering joints on dynamics behavior

4.1. Effect of stiffness of steering joints on critical velocity

In this paper, five typical worn tread matches with measured rail 60D. The range of longitudinal stiffness of axle box steering joints is 0.5~35.5MN/m, and range of lateral stiffness of axle box steering joints is 1~10.5MN/m. The simulated result of critical speed under variable stiffness of steering joints is shown in figure 3. Here, critical speed is the convergent speed under the actual track excitation, that is, railway vehicle first runs on a section of the rough track excitation line,
and then removes the track excitation, and observes whether railway vehicle converges. Track excitation adopts special track spectrum. The excitation length is set at 300m.

According to the figure 3(a), with the increment of longitudinal stiffness of axle box steering joints, critical speed of vehicle gradually increases, and when longitudinal stiffness increases above 17.5MN/m, the incremental rate of critical speed tends to be stable. In addition, with the increment of equivalent conicity of wheel profile, under same longitudinal stiffness of steering joints, the smaller the equivalent conicity, the smaller the corresponding critical speed of railway vehicle. However, when the equivalent conicity increases to 0.16, meanwhile longitudinal stiffness of steering joints is less than 22.5MN/m, the critical velocity still follows the above changing rule, that is, with the increment of longitudinal stiffness of steering joints, critical velocity gradually increases. While critical speed of vehicle does not remain stable until longitudinal stiffness of steering joints increases to 22.5MN/m. It is shown that there is an optimal equivalent conicity or an optimal equivalent conicity zone in wheel and rail wear process. According to the figure 3(b), with the increment of lateral stiffness of steering joints, the critical speed tends to increase first and then decrease, finally tends to be stable near 5MN/m, which reaches the maximum when the stiffness is 2.5MN/m. Similarly, with the increment of equivalent conicity, the critical speed is smaller under the same lateral stiffness.

4.2. Effect of stiffness of steering joints on stability

The figure 4 shows effect of stiffness of axle box steering joints on stability. Where, the line is set as a straight line, speed is set as 400km/h, and the track excitation adopts the measured WuGuang line.

According to the figure 4(a), longitudinal stiffness of axle box steering joints has a huge impact on lateral stability of railway vehicle. When longitudinal stiffness of steering joints is small, the railway vehicle is prone to instability, and lateral stability index even exceeds the limit 2.5. So strict precautions should be taken in actual production. With the increment of longitudinal stiffness of steering joints, lateral stability of railway vehicle is gradually optimized, and reaches stability after about 17.5MN/m. In particular, in the early wheel and rail wear stage, equivalent conicity is small, and stability stiffness required which lateral stability tends to be stable is also small. However, with the increment of equivalent conicity, the longitudinal stiffness required which railway vehicle tends to be stable gradually increases. According to the figure 4(b), at low conicity, lateral stiffness of axle box steering joints has little influence on lateral stability of railway vehicle, and with increment of conicity, the influence of lateral stiffness of steering joints on lateral stability increases gradually.

In addition, under same longitudinal and lateral stiffness of steering joints, with the increment of equivalent conicity, lateral stability of vehicle gradually deteriorates. which indicates, with the increment of service mileage of railway vehicle and increment of wheel and rail wear, that lateral stability of railway vehicle gradually decreases, and preventive measures should be taken to control. The sensitivity of vertical stability to equivalent conicity and stiffness of axle box steering joints is low, it is not discussed here.

![Figure 4. Relationship between stiffness of steering joints and lateral stability](image-url)
4.3. Effect of stiffness of steering joints on safety

The figure 5 and 6 shows effect of stiffness of axle box steering joints on vehicle safety. Where, rail line is set as a curve, and curve parameters are set as follows: 300m linear section, 350m circular section, 7000m curve radius, 110mm superelevation. The speed of passing curve is 300km/h, and track excitation adopts the measured WuGuang line.

According to the figure 5(a), longitudinal stiffness of steering joints has a significant impact on vehicle safety. According to the above analysis, when longitudinal stiffness of steering joints is too small, the bogie will have an obvious hunting movement, which will result in a large lateral impact between wheel and rail, and cause a sharp increment of lateral force of wheel set. With the increment of longitudinal stiffness of steering joints, constraint effect from the bogie on wheel set is strengthened, which can effectively restrain yaw movement of wheel set, and reduce impact of wheel on the rail. Therefore, lateral force of wheel set gradually decreases and eventually tends to be stable.

According to figure 5(b), at mild wear and low conicity, lateral stiffness of steering joints has little influence on lateral force of wheel set. However, with the increment of equivalent conicity, lateral stiffness of steering joints and lateral force of wheel set are positively correlated. Obviously, under same longitudinal and lateral stiffness of steering joints, with the increment of equivalent conicity, lateral force of wheel set increases gradually. It indicates, with the increment of wheel and rail wear, that safety of railway vehicles begins to deteriorate, and measures should be taken to prevent it.

![Figure 5](image5.png)

**Figure 5.** Relationship between stiffness of steering joints and lateral force of wheel set

According to the figure 6(a), when longitudinal stiffness of steering joints is too small, the bogie will move in a hunting movement, and produce a large lateral impact on the rail, and lead to an increment in derailment coefficient. With the increment of longitudinal stiffness of steering joints, constrained force from bogie on wheel set is strengthened, and inhibits the yaw movement of wheel set, so rail impact from wheel is reduced. Therefore, derailment coefficient gradually decreases and eventually tends to be stable.

![Figure 6](image6.png)

**Figure 6.** Relationship between stiffness of steering joints and derailment coefficient
According to the figure 6(b), at low conicity, lateral stiffness of axle box steering joints has little impact on derailment coefficient. However, when equivalent conicity is large, with the increment of lateral stiffness of axle box steering joints, derailment coefficient increases quickly. With the increment of equivalent conicity, derailment coefficient increases obviously under the same longitudinal and lateral stiffness.

5. conclusion

(1) The evolution of wheel tread after continuous wear is compared, and it is found that position of wheel wear is basically concentrated in the range of ±20mm from rolling circle and the waist of flange, which has a significant impact on the equivalent conicity. With the increment of operating mileage, the wear depth and width increase gradually.

(2) Wheel and rail wear has obvious influence on the critical speed, stability and safety of railway vehicle. With the increment of wheel and rail wear, critical speed generally decreases. According to simulation, there is the optimized conicity in wheel and rail wear progress. Meanwhile hunting stability of railway vehicle increases with increment of conicity gradually, but vertical stability remains unchanged. The operating safety indexes, such as lateral force of wheel set and derailment coefficient, also increase with the increment of wheel and rail wear.

(3) The stiffness of axle box steering joints has obvious effect on the critical velocity of railway vehicle. With the increment of longitudinal stiffness of axle box steering joints, critical speed increases gradually, and the increment of critical speed tends to be stable when longitudinal stiffness of steering joints reaches a certain value. With the increment of lateral stiffness of axle box steering joints, critical speed tends to increase first and then decrease, and finally tends to be stable around 5MN/m, which reaches the maximum when lateral stiffness of steering joints is 2.5MN/m.

(4) The stiffness of axle box steering joints has obvious effect on the lateral stability. When longitudinal stiffness of steering joints is small, railway vehicle is prone to instability, and lateral stability index is relatively large. With the increment of longitudinal stiffness of steering joints, lateral stability is gradually optimized, and finally reaches stability after about 17.5MN/m. Laterally stiffness of steering joints has little influence on lateral stability of railway vehicle. The effect of stiffness of steering joints on railway vehicle safety is basically consistent with the stability, so that won't be covered again here.

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