Effect of Wheelset Steering Stiffness Difference on the Dynamics Performance of a High-speed Railway Vehicle

Tao Cui¹, Qi Wang¹, Xuegang Liu¹, Sijie Chen²*
¹ Technology Research Center, CRRC Tangshan Co., Ltd., Tangshan, 063035, China
² State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, 610031, China
*Corresponding author’s e-mail: sijie_chen163@163.com

Abstract: In order to study the influence of steering difference of wheelsets among one bogie on the dynamics performance of vehicle, a highly nonlinear dynamics model of the high-speed railway vehicle multi-body system is built. In numerical simulations, the combined condition of taking the upper and lower limits of the steering stiffness of wheelset is investigated, respectively. It shows that the effect of wheelset steering stiffness on the dynamic performance is not significant. Its influence on the lateral vibration of bogie frame, hunting stability of vehicle, operation safety when negotiating curved tracks and wheel wear is generally within 5%. Its influence on the maximum lateral and vertical acceleration of carbody is generally within 10% and the influence range of specific cases is within 20%. For all the numerical cases, the vehicle dynamics indexes all meet the required limit.

1. Introduction
Vehicle dynamics performance is an eternal topic in railway transportation. Bogie is an important safety part of railway vehicles. It needs to steer vehicles and bear various impact loads. Bogie suspension parameters have a significant impact on vehicle dynamics performance. Therefore, many domestic and foreign scholars have studied the wheelset steering stiffness of a bogie. Chi et al.[1] first analyzed the influence of the primary and secondary suspension parameters on the dynamics performance of a high-speed passenger vehicle in time domain, then analyzed the influence of the secondary system suspension parameters on the vibration mode of the carbody in the frequency domain. Wu et al. [2] established the dynamics model of high-speed railway vehicle concerning suspension failure, and conducted wheel-rail contact geometric relations and dynamics simulation analysis for the new and the worn wheel-rail matchings. Zhang et al. [3], by establishing a vehicle system dynamics model with variable stiffness of wheelset steering and comparing fixed stiffness of wheelset steering, analyzed the hunting stability and curve negotiation performance. Qi et al. [4] compared and analyzed the curve negotiation performance of the fixed stiffness model and the variable stiffness model, and calculated the wheel wear depth by the ZOBORY wear model. Zhu and Wu [5] studied and analyzed the influence of longitudinal and lateral stiffness of a series on vehicle dynamics performance. Wickens [6] summarized the research progress of railway vehicle bogies and other forms of walking devices, with particular reference to the conflict between stability and curving. Taking high-speed railway vehicles as the research object, Lee and Cheng [7] analyzed the hunting stability of axle box during longitudinal active control, and focused on the influence of axle box suspension parameters on vehicle dynamics performance. Park et al. [8] conducted a comprehensive
study on the lateral stability of vehicles by adopting the method of proportional change of the primary lateral positioning stiffness, secondary lateral stiffness and damping parameters. Zboinski [9] studied the curve negotiation of railway vehicle, analyzed the dynamics performance of a series of suspension parameters on the curve negotiation, and studied the influence of suspension parameters on the curve negotiation stability.

Therefore, this work takes a 400 km/h high-speed railway vehicle as an example, a highly nonlinear dynamics model of the high-speed railway vehicle multi-body system is built, analyzes the influence of wheelset steering stiffness difference on the dynamics performance of the vehicle, takes into account the combination of the upper and lower limits of the wheelset steering stiffness, and calculates the hunting stability, riding comfort and operation safety of the motor train and trailer respectively.

2. The dynamical model of vehicle

The 400 km/h high-speed train is a complex multi-body system, which not only has the interaction force and relative motion between the components, but also has the interaction relationship between wheels and rails. The following assumptions are made when establishing the mathematical model of the vehicle system.

1) The elasticity of components such as wheelset, frame and carbody is much smaller than that of suspension system, which is considered as rigid body, i.e. the elastic deformation of each component is ignored.

2) The interaction between adjacent vehicles is not considered, that is, only single vehicle model is considered.

The dynamical model of the 400 km/h high-speed railway train is established, which includes the model of the motor train and the model of the trailer, and where the nonlinear wheel-rail contact geometrical relationship, the wheel-rail interaction force and the suspension parameter are considered. The carbody, bogie and wheelset all have 6 degrees of freedom corresponding to the movements along the three shifting directions (longitudinal, lateral and vertical) and the rotations around these axes (rolling, pitching and yawing). The swing-arm has one degree of freedom corresponding to the pitch movement. Therefore, each trailer has 50 degrees of freedom, and each motor train has 78 degrees of freedom.

The dynamical equation of the vehicle system[10] is:

$$M\ddot{x} + C\dot{x} + Kx = P(\dot{x}, \ddot{x}, x) + Te$$  \hspace{1cm} (1)

![Figure 1. The dynamical model](image)

3. Influence of the wheelset steering stiffness difference on the dynamics performance

The dynamical model of vehicle is adopted to analyze the influence of the wheelset steering stiffness on the dynamic performance by taking into account the conditions of the vehicle passing through the small radius curve at low speed and the large radius curve at the high speed, taking into account the small wheelset equivalent conicity of the new wheel and the large wheelset equivalent conicity of the worn wheel, respectively. In the following tables and graphs, it is defined:

1) “small R new” presents the vehicle passes through the radius of 250 m at 30 km/h without superelevation curve, and adopts the matching relationship of wheel rail with small wheelset equivalent conicity under the new wheel tread.
2) “small R wear” presents the vehicle passes through the radius of 250 m at 30 km/h without superelevation curve, and adopts the matching relationship between wheels and rails with large wheelset equivalent conicity under the worn wheel tread.

3) “large R new” presents the vehicle passes through a curve of 8000 m with a radius and 160 mm with a superelevation at 400 km/h with a small wheelset equivalent conicity under the new wheel tread.

4) “large R wear” presents the vehicle passes through a curve of 8000 m with a radius and 160mm with a superelevation at 400 km/h with a large wheelset equivalent conicity under the worn wheel tread.

Considering the longitudinal and lateral wheelset steering stiffness errors +15 % and -15 % respectively, there are 16 combinations of the positions of four wheelset steering nodes on a bogie. Considering the synchronous change of longitudinal and lateral stiffness of wheelset steering, the change rule of the front and rear bogies is the same. In addition, there are a total of 17 cases when each wheelset steering node takes the nominal wheelset steering stiffness. The 17th case (the last case in the figure) is the nominal wheelset steering stiffness.

Through the research, it was found that there was little difference between the trailer and the motor train results. Therefore, only the trailer analysis results are shown below.

3.1. Hunting stability analysis
As can be seen from the Figure 2, when the vehicle passes through the curve with a radius of 8000 m at 400 km/h, the lateral acceleration of bogie frame is relatively large, reaching about 0.4 g. In other cases, the acceleration is less than 0.2 g. The wheelset steering stiffness difference has a slight influence on the lateral acceleration of the bogie frame when running at high speed under the large wheelset equivalent conicity tread, but the influence range is within 0.05 g.

![Figure 2. Lateral acceleration on the bogie frame end](image)

3.2. Ride comfort analysis
It can be seen from Figure 3 that the lateral and vertical Sperling indexes, as well as the maximum values of the lateral and vertical accelerations are relatively large when the vehicle is running at high speed. The wheelset steering stiffness difference has a certain effect on the vibration acceleration of carbody when running at high speed under the large wheelset equivalent conicity tread. The influence range of Sperling index is generally less than 5 %, the influence range of other indexes is generally less than 10 %, and the influence range of individual indexes under special cases is less than 20 %. The dynamics performance indexes of bogie wheelsets under nominal wheelset steering stiffness is in the middle.
3.3. Operation safety index and wear number

Figure 4 to Figure 6 below respectively show the influence of the wheelset steering stiffness difference among one bogie on the lateral force of wheelset, derailment coefficient and wheel wear number. It can be seen from the figure that under the cases of "large R new" and "large R wear", the wheelset steering stiffness difference has basically no influence on the lateral force of wheelset, derailment coefficient and wheel wear number. Under the cases of "small R new" and "small R grinding", the wheelset steering stiffness difference has no obvious influence on the lateral force of wheelset, derailment coefficient and wheel wear number, and its variation range is within 5 %.
4. Conclusions
Considering the typical wheel-rail matching state with small wheelset equivalent conicity of the new tread and large wheelset equivalent conicity of the worn tread, the small radius curve of the track and the large radius curve of the positive line, the influence of the wheelset steering stiffness error on the dynamics performance of the motor vehicle and trailer is analyzed.

From the dynamic analysis, the following conclusions can be drawn.
1) The effect of wheelset steering stiffness on the dynamics performance is not significant. It is found that the influence range of lateral acceleration on the bogie frame end, Sperling index, operation safety index and wheel wear number is generally within 5%, the influence range of maximum lateral and vertical acceleration of carbody is generally within 10%, and the influence range of specific conditions is within 20%.
2) When wheelset steering stiffness difference takes the nominal value, the dynamics performance is in the middle of various error states.
3) For all the numerical cases, the vehicle dynamics indexes all meet the required limit.

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