Effect of Variable Wheelset Steering Stiffness and Yaw Damper Damping on Hunting Stability

Lixin Zhang¹, Qi Wang²*, Yunhai Yu³

¹CRRC Tangshan Co., Ltd. Tangshan, China
²CRRC Tangshan Co., Ltd. Tangshan, China
³CRRC Tangshan Co., Ltd. Tangshan, China

*Corresponding Author e-mail: wangqi2@tangche.com

Abstract—Due to the track curvature and irregularities difference, a high-speed dedicated railway vehicle running on a high-speed railway cannot achieve a good dynamics performance when it is operated on an existing railway for conventional low-speed railway vehicle. Then an adaptive bogie which can adjust its suspension parameters, like the steering stiffness of wheelset and the damping of yaw damper, is regarded as a solution to make the high-speed train be operated on an existing railways. In this investigation, a highly nonlinear dynamics model of the adaptive bogie vehicle multi-body system is built to study the effects of wheelset steering stiffness and yaw damper damping on the vehicle dynamics. Both a straight track passing and curved tracks negotiating scenarios are considered to examine the expected range of stiffness and damping when the bogie was operated those two kinds of railways. It shows that reducing the steering stiffness of wheelset leads to a significant decrease in the critical speed of vehicle, and the critical speed of vehicle decreases significantly when the yaw damper damping is less than 500 kN·s/m. In case of wheel wear, the smaller the wheelset steering stiffness or the yaw damper damping is, the lower the critical speed of vehicle is. Through the analysis, the limit values of wheelset steering stiffness and yaw damper damping are proposed. When the adaptive bogie vehicle operates on the existing track, the lower limit values of wheelset steering stiffness and yaw damper damping are 12 MN/m and 200 kN·s/m respectively.

1. INTRODUCTION

Vehicle dynamics performance is an eternal topic in railway transportation. It has complex boundary condition excitation of the line when the vehicle operates. Bogie is an important safety component of railway vehicle, and the railway network and bogie technology in different countries are different [1]. Therefore, it is of great significance and engineering application value to study the suspension parameter technology of adaptive bogie under different line characteristics. At present, many domestic and foreign scholars have done a lot of study. Chi et al. [2] 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 secondray system suspension parameters on the vibration mode of the carbody in the frequency domain. Shi et al. [3] studied the changes of wheel wear, hunting stability, Sperling and vibration characteristics with operation mileage, line conditions, ambient temperature, train operation speed and other parameters. Wu et al. [4] 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. [5], 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. Modeling with SIMPACK, He and Wang [6] studied the influence of yaw damper series stiffness on critical speed under different longitudinal wheelset steering stiffness and equivalent conicity. Sun et al. [7] derived the analytical expression of linear critical speed of rigid bogie with yaw damper, and studied the influence of series stiffness and structural damping of yaw damper on critical speed under different equivalent conicity. Wickens [8] 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 [9] 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. [10] 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 [11] 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 an adaptive bogie vehicle (motor train) as an example, a highly nonlinear dynamics model of high-speed railway vehicle multi-body system is built, analyzes the influence of variable wheelset steering stiffness and yaw damper damping on hunting stability, takes into account the vehicle passing through a straight-line track and a curved track in the condition of new wheel and worn wheel, and calculates the hunting stability of the motor train respectively.

2. THE DYNAMICAL MODEL OF VEHICLE

The 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.

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

The dynamical model of the high-speed railway train (motor train) is established, and where the nonlinear wheel-rail contact geometrical relationship, the wheel-rail interaction force and the suspension parameter are considered. The carbody, bogie, wheelset and primary tie rod 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 motor train has 98 degrees of freedom.

The dynamical equation of the vehicle system [12] is:

\[ M\ddot{x} + C\dot{x} + Kx = P(\dot{x}, \dot{x}, x) + Te \]  

(1)

Figure 1. The dynamical model
3. **INFLUENCE OF VARIABLE STIFFNESS AND DAMPING ON HUNTING STABILITY**

The dynamical model of vehicle is adopted to analyze the influence of variable wheelset steering stiffness and yaw damper damping on hunting stability by taking into account the conditions of the vehicle passing through a straight-line track and a curved track, and taking into account the conditions of a new wheel and a worn wheel.

Considering the stiffness range of wheelset steering from 2 MN/m to 20 MN/m and the damping range of yaw damper from 100 kN·s/m to 1 MN·s/m, the hunting stability of vehicle on a straight-line track, and a curved track with a radius of 2000 m and a superelevation of 140 mm in the condition of the new wheel and the worn wheel is analyzed.

3.1. **Influence of variable wheelset steering stiffness on hunting stability**

As shown in Figure 2, it is the critical speed of vehicle in a new wheel and a worn wheel respectively when the wheelset steering stiffness is changed, of which 18 MN/m is the nominal wheelset steering stiffness. It can be seen in the figure that reducing the wheelset steering stiffness leads to a significant decrease in the critical speed of vehicle. When the wheelset steering stiffness is reduced to 2 MN/m, the critical speed of vehicle in the new wheel is reduced to 223 km/h, and the critical speed of vehicle in a worn wheel is reduced to 200 km/h, which is larger than the speed limit of 160 km/h on the existing line. Therefore, the wheelset steering stiffness can be reduced to 2 MN/m, which can meet the requirements of hunting stability while achieving the goal of low wheel-rail force and low wear at the same time.

Figure 3 show the maximum lateral acceleration at the bogie frame end when the vehicle passing through a curved track at different speeds in the condition of the variable wheelset steering stiffness. In case of wear wheel, when the vehicle speed is below 160 km/h, the maximum lateral acceleration at the bogie frame end is less than 0.4 g, which can be judged to meet the hunting stability requirements when the vehicle passing through a curved track; in case of wear wheel, the smaller the wheelset steering stiffness is, the lower the critical speed of vehicle is, and when the wheelset steering stiffness is 2 MN/m, the passage speed satisfying the hunting stability is 105 km/h, but the equilibrium speed through a curved track is 160 km/h, so in order to meet the hunting stability requirements, the wheelset steering stiffness should be larger than 12 MN/m.

![Figure 2. Critical speed on straight-line track](image-url)
3.2. Influence of variable yaw damper damping on hunting stability

As shown in Figure 4, is the critical speed of vehicle in the condition of variable yaw damper damping in a new wheel and a worn wheel, of which 800 KN·s/M is the nominal yaw damper damping. It can be seen in the figure that when the yaw damper damping is less than 500 kN·s/m, the critical speeds of vehicle decrease significantly. Among them, when the damping is reduced to 100 kN·s/m, the critical speed of vehicle in the new wheel is reduced to 328 km/h, and the critical speed of vehicle in the worn wheel is reduced to 275 km/h, which is far larger than the speed limit of 160 km/h on the existing track. Therefore, when the yaw damper damping is reduced to 100 kN·s/m, it can achieve the goal of low wheel-rail force and low wear and also meet the requirements of hunting stability.

Figure 5 show the maximum lateral acceleration at the bogie frame end when the vehicle passing through a curved track at different speeds in the case of variable the yaw damper damping. It can be seen that in case of wear wheel, when the vehicle speed is less than 160 km/h, the maximum lateral acceleration at the bogie frame end is less than 0.4 g, which can be judged to meet the hunting stability requirements when the vehicle passing through a curved track; in case of wear wheel, when the yaw damper damping is 100 kN·s/m, the passage speed satisfying the hunting stability is 145 km/h, because the equilibrium speed of passing through a curved track is 160 km/h, so it is meet the hunting stability requirements, and the yaw damper damping should be larger than 200 kN·s/m.
4. CONCLUSIONS

Considering the typical wheel-rail matching state with a small wheelset equivalent conicity of a new wheel tread and a large wheelset equivalent conicity of a worn wheel tread, and a straight-line track and a curved track, the effects of the variable wheelset steering stiffness and yaw damper damping on the running stability of a high-speed vehicle are analyzed. When the adaptive bogie high-speed railway vehicle operates on the existing line, the lower limit value of wheelset steering stiffness is 12 MN/m, and the lower limit value of yaw damper damping is 200 kN·s/m.

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