Dynamics Performance Analysis of a 400 km/h EMU

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Abstract—In order to study the dynamics performance of a 400 km/h high-speed train, a nonlinear dynamics model of a 400 km/h EMU (Electric Multiple Units) composed of three vehicles is built. The dynamics performance of those vehicles under new and worn wheel/rail interactions are examined and compared through numerical analysis. It shows that the lateral acceleration on the middle vehicle is 23% smaller than that of the head vehicle and the tail vehicle under a new tread condition; in case of wheel wear, the lateral acceleration on the middle vehicle is 31% smaller than that of the head vehicle and the tail vehicle; the vertical wheel/rail force of the middle vehicle is 10.5% larger than that of the head vehicle and the tail vehicle; the lateral wheelset force under the worn wheel case is 52% greater than that under the new wheel condition. In all numerical cases, the vehicle dynamics indexes all meet the required limits which proves that the 400 km/h high-speed train is properly designed.

1. INTRODUCTION
In the past, the simulation research on the dynamic performance of high-speed train is mostly limited to a single vehicle.¹² In order to further study the dynamic performance of the train and master the dynamic differences of vehicles in different positions, it is necessary to establish a dynamic model composed of multiple vehicles. Liu and Zeng ³ built a train dynamics model including three trailers to study the riding stability of high-speed trains. Luo et al.⁴ considered the situation of single vehicle, 5-vehicle formation and 7-vehicle formation, and analyzed the riding stability of train operation. It shows that the riding stability of the head and the tail train is the worst, and the middle train is better. Chi et al.⁵ considered the coupling relationship among the longitudinal, lateral and vertical performance of the train, and built a three-dimensional spatial coupling dynamic model of the long and heavy-duty train. The simulation results show that under the traction condition, the dynamic performance of the vehicle at the head and tail of the train is worse than that of the vehicle in the middle of the train; under the braking condition, the dynamic performance of the vehicle in the middle of the train is worse than that of the vehicle at the head and tail of the train. Li et al.⁶ built the dynamic model of three vehicles high-speed EMU, and discussed the influence of damper between vehicles on the riding stability, vibration acceleration and curve passing safety performance of EMU. Yang and Lin ⁷ ⁸ built the high-speed train model of multiple vehicles by the finite method, and carried out a series of research on the problems related to train vibration. Luo et al.⁹ proposed a simple and more-accurate nonlinear rubber spring model which is more suitable for the vehicle dynamics analysis of a high-speed train. The proposed model contains three components, an elastic
force, damper force and the Maxwell element, which are used to present the frequency and amplitude dependence.

Therefore, taking the high-speed railway vehicles with speed of 400 km/h as an example, this paper set up a nonlinear dynamic model of high-speed train composed of three vehicles, including the motor vehicle model and trailer model. Considering that the wheel rail matching relationship has great influence on the dynamic performance\cite{10}\cite{11}, the riding stability, riding comfort and riding safety of the head vehicle, the middle vehicle and the tail vehicle are calculated respectively under different wheel rail matching combinations. The differences of dynamic performance among the head vehicle, the middle vehicle and the tail vehicle are analyzed as well as the influence of wheel rail matching relationship on the vehicle dynamic performance.

2. THE DYNAMICAL MODEL OF VEHICLE

The high-speed train with a speed of 400 km/h is a complex multi-body system, which not only has the interaction force and relative motion between the various components, but also the interaction between the wheel and the rail. In order to better simulate the running performance of a high-speed train runs at 400 km/h and above, a mathematical model for coupling the lateral and vertical motion of vehicles is built. This high-speed train dynamics model consisting of three vehicles, including the motor vehicle model and the trailer model. The trailer model consists of 1 body, 2 bolsters, 2 frames, 4 wheel sets and 8 swing-arms. The motor vehicle model consists of 1 body, 2 bolsters, 2 frames, 4 wheel sets, 8 swing-arms, 2 motors, large and small gears, a gear box and a motor rotor. The vehicle body, frame and wheel pair take 6 degrees of freedom; the bolster beam is fixedly connected with the vehicle body, so there is no independent degree of freedom; the swing-arm takes 1 pitch degree of freedom; the transmission system of the motor vehicle has only pitch degree of freedom. There are 50 degrees of freedom for a trailer model, and 54 degrees of freedom for the motor vehicle. The wheel tread profile adopts LMB_10 tread and worn tread (measured worn tread of LMB_10 with the equivalent taper of about 0.35), and the rail adopts standard CN60 rail and grinding rail profile. The nonlinear geometric relationship between wheel and rail is processed by interpolation method, and the nonlinear force is calculated by Kalker nonlinear creep theory. Damping characteristics of a damper and the lateral stop damping characteristics of the secondary suspension are also non-linear. The dynamics model of the train with three vehicles is plotted in Figure 1, and the equation of motion for the train system can be presented by\cite{12},

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

(1)

Figure 1. The dynamical model

3. DYNAMIC PERFORMANCE ANALYSIS

The dynamic performance of a 400 km/h train under different wear conditions were simulated. One wear state is that the LMB_10 tread is matched with the CN60D polished rail, so that the equivalent taper is the lowest; another wear condition is that the worn wheel tread matches the standard CN60 rail, so the equivalent taper is relatively large. The dynamic performance analyzed includes riding stability, riding comfort and riding safety indexes.
3.1. Riding stability analysis

The method of riding stability analysis is to filter the lateral acceleration at the end of the frame with 10 Hz low-pass, and analyze the maximum value of the lateral acceleration at the end of the frame. In the analysis of the lateral acceleration of the frame, the maximum acceleration after filtering is taken directly, without considering the number of peaks, and the filtering range is wider than the actual one, which is to make the analysis results safer.

As can be seen from the Figure 2:

- Within the speed range of 400 km/h, under the new tread of LMB_10, the maximum lateral acceleration (single peak value) at the end of the frame is less than 0.35g; under the worn tread, the maximum lateral acceleration (single peak value) at the end of the frame is less than 0.6g.
- The maximum lateral acceleration (single peak value) at the end of middle vehicle frame is less than that of the head vehicle and the tail vehicle. When the speed is 400 km/h, under the new tread condition, the corresponding value of the middle vehicle is 23% smaller than that of the head vehicle and the tail vehicle; under the worn tread condition, the corresponding value of the intermediate vehicle is 31% smaller than that of the head vehicle and the tail vehicle.

3.2. Riding comfort analysis

Through the dynamic simulation, the lateral stability indexes, vertical stability indexes and comfort indexes of the front end and rear end of each vehicle body are calculated respectively. All kinds of calculation parameters are named meaning values. Because the Sperling index of the head vehicle, the middle vehicle and the tail vehicle are basically the same, only the Sperling index of the head vehicle are used for drawing.

As can be seen from the Figure 3 and the Figure 4:

- The horizontal and vertical Sperling indexes of LMB_10 tread and worn tread are less than 2.5, and the comfort indexes are less than 2.0.
- The difference of the comfort index value of the head vehicle, the middle vehicle and the tail vehicle on the worn tread is smaller than that of the head vehicle, the middle vehicle and the tail vehicle on the new tread.
3.3. Riding safety analysis

Through the dynamic simulation, the wheel/rail force of the vehicle system are calculated respectively, and the maximum values of the lateral wheelset force, the wheel-rail vertical force, the derailment coefficient and the wheel load reduction rate are obtained. All kinds of calculation parameters are named meaning values.

As can be seen from the Figure 5:
- In the speed range of 400 km/h, all safety indexes of wheel axle lateral force, wheel rail vertical force, derailment coefficient and wheel load reduction rate meet the requirements of dynamic standard, and there is enough safety margin.
- For the four indexes of wheel axle lateral force, wheel rail vertical force, derailment coefficient and wheel load reduction rate, the value corresponding to the worn tread is greater than that corresponding to the new tread, and the value corresponding to the middle vehicle is greater than that corresponding to the head vehicle and the tail vehicle. Among them, the maximum vertical wheel rail force of the middle vehicle is 10.5% greater than that of the head vehicle and the tail vehicle, and the maximum lateral force of the axle under the worn tread condition is 52% greater than that under the new tread condition.

Figure 5. Riding safety indexes
4. CONCLUSIONS
The multibody dynamic model of a 400 km/h high-speed train composed of three vehicles is built to examine their dynamics behaviour. Under the new and worn wheel/rail interaction conditions, the dynamic performance differences among vehicles is analyzed, and the following conclusions can be drawn.

- Under 400 km/h, the vehicle's riding stability indexes, riding comfort indexes and riding safety indexes meet the required limits, which proves that the 400 km/h high-speed train is properly designed.
- For riding stability, the new tread is better than the worn tread, and the middle vehicle is better than the head vehicle and the tail vehicle; for riding comfort, the difference between the new tread and the worn tread is not big, and the difference between the three vehicles is not big; for riding safety, the new tread is better than the worn tread, and the head vehicle and the tail vehicle are better than the middle vehicle.

ACKNOWLEDGEMENTS
This work was partially supported by National Key R&D Program of China (#2018YFB1201702) and National Natural Science Foundation of China (#11790282).

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