A brief review of modelling and simulation of three dimensional train system dynamics

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Abstract

With the development of computer and software, the dynamic modeling and analysis of train system is more and more convenient and accurate. This paper summarizes these two problems of researchers through three-dimensional modeling and analysis. First, modeling of three-dimensional train dynamics, the factors considered in the model, and the results proved by the model are introduced and secondly, research on train dynamics under traction or braking conditions. Dynamic analysis software have multi-carriage train modeling and analysis functions, refreshers use these commercial software, added actual consideration of factors to the three-dimensional model, have solved reality problems effectively.

Keywords: Train; Three dimensional; System dynamics; Model

1. Introduction

Being different from the train longitudinal dynamics, the three dimensional (3D) train dynamics research focuses more on the wheel/rail lateral and vertical dynamic problems of the train, such as the train hunting stability, the vehicle derailment safety, the wheel load reduction, ride comfort and so on. According to the specific analysis requirements, the scholars have established many dynamic models with different degree of freedoms (DOF), including the single or multi vehicle model with the full DOFs, the train dynamics model with the simplified DOFs and the detailed train model et al. The analysis tool early used was the special program code for the particular research object. With the development of computer technology and computational multi-body system dynamics, between late 1980s and early 1990s, the SIMPACK, ADAMS, NUCARS, VAMPIRE and other commercial software packages were applied in the railway vehicle dynamics analysis. The development and application of dynamic software has brought great convenience to the train system mathematical modeling and the dynamic analysis, contributing to the co-simulation technique with other analysis software, such as Matlab, AMESim etc. So far, both the mature commercial software packages and the special computing programs developed by the users have become the predominant analysis tool. Also, the focused problems are expanded from the simple horizontal or vertical dynamic problems to the train three dimensional dynamics. Research contents are wider, and the factors considered are more complicated. Detailed research progress is given in the following.

2. Modeling of three-dimensional train dynamics

With the ever development of freight transportation, the heavy-haul train dynamics develops at the aspects of the field test and theoretical analysis. Both the severe wheel/rail force and longitudinal impulse effect are the distinguishing features of the heavy-haul train, and many scholars carry out research on the train operation safety under the coupler force. El-Sibaie [1] introduced a method to evaluate wagon derailment stability under the coupling force. Durali [2-4] studied the train derailment safety in the emergency braking saturation, and every vehicle has more than 40 DOFs. To improve computational efficiency, an improved mixed train dynamic model was established, in which one wagon had 48 DOFs and the rest wagons had fewer DOFs. In order to achieve the derailment inspection, Plainer et al. [5] evaluated various signals on locomotive by means of simulation. And also a derailment test was carried out. It was found out that the method would fail if the distance between a derailed vehicle and the locomotive was more than 10 vehicles, or the number of central fully loaded vehicle was less than 10. Jeong [6] established a two-dimensional train model to study train behavior after derailing accidents, in which the wheel/rail relationship was simplified as the friction forces between the vehicle and ground. Cole [7] pointed out that the longitudinal coupler force might lead to freight trains rollover, wheel climb rail and freight train taking...
off the line. In the former longitudinal dynamics model, quasi static coupler lateral force was taken into account. Wu et al. [8], established a detailed model of locomotive coupler and buffer model by considering the friction in the hook end, and studied the dynamic behavior of the locomotive and drawbuffer system under the coupler-pressing force.

To study the marshaling of high-speed train, Ling et al. [9] established a three-dimensional dynamic model, in which the force of non-linear buffer device, the longitudinal shock absorbers between carriages and tight-lock vestibule diaphragm were taken into account. Chen [10] pointed out that longitudinal force caused by coupler force would affect lateral force when the coupler has a swing angle, track irregularity may also cause a greater degree of lateral movement of the coupler longitudinal force, and the derailment caused by coupler force may have many forms, the simulation analysis also showed that although the maximum of coupler longitudinal force is 1135 kN when the train was braking, for the train used a non-midline coupler, great coupler swing angle caused a large wheel / rail lateral load, the load overcome the rail resistance and caused the rails to roll over.

In order to achieve the simulation analysis of the long and heavy-haul train, Zhang et al. [11-12], developed the train dynamics simulation software TPL train, in which each vehicle used the detailed 3D dynamic model by considering three directional coupler forces. To study heavy-duty train dynamics in the condition of air brake, the air braking simulation system was introduced into the train dynamics simulation software. At the aspect of train-track coupled dynamics, Liu et al. [13,14] firstly analyzed the basic principles of the inter-vehicle interaction and train-track dynamic interaction. Based on theories of train longitudinal dynamics and vehicle-track coupled dynamics, the three-dimensional dynamic model of the heavy-haul train–track coupled system was established, as shown in Fig. 1. And the theoretical model was verified by the running test results. Xu [15] et al., analyzed the rotation behavior of the train’s coupler system and its effect on the dynamic behavior of the middle locomotive when operating on tangent and curved tracks. A 3D train model was established, which included detailed coupler and draft gear. The friction characteristics of the coupler knuckles, the hysteretic characteristics of the rubber draft gear model, and the alignment-control characteristics of the coupler shoulder were considered. The results proved that decreasing the maximum of coupler free angle can improve operational performance and safety performance of trains.

3. Research of train dynamics in traction or braking conditions

For the trains in the operation of traction or braking conditions, some scholars focused on the impact of traction and braking torque on the dynamic performance of the train. According to the creep state between wheel and rail in the case of adhesion limit when train in traction condition, Polach [16,17] proposed a wheel/rail tangential force calculation method that can be applied to the condition of large creep, and it had been proved through test. Grassie and Elkins [18] pointed out that huge tangential force between the wheel and rail was mainly due to traction and curve negotiation, the wheel/rail forces of two-axle bogie when passing through the curve of 600–1800 m radius was studied. For the non-power bogie, the tangential force reached the maximum at the high-wheel of the guide wheelset, achieved minimum at the high-wheel of shaft, the tangential force of the two wheelsets was larger under the traction condition. And as the traction increased, the guiding performance of the wheel would be worse, increasing the degree of over high helped to redistribute the creep forces of the four wheels of the bogie, make each creep force similar, and reduce maximum creep force. Dhanasekar [19] studied the influence of the braking torque on the dynamic performance of freight train, studies have shown that the effect of braking torque would change the vehicle dynamic characteristics in a certain aspect, for example, when track exist horizontal irregularity, large braking torque can lead to larger wheel load reduction, but there was no brake torque or brake torque was small, wheel load reduction phenomenon was not obvious.

Aiming at calculating wheel/rail force of braking condition in train dynamics simulation, Handoko [20,21] proposed an inertial reference coordinate system, in order to study dynamic behavior of train when the traction and braking torque exit, a simulation program was developed, study’s object was train bogie, as shown in Fig. 2, the method to calculate wheel/rail contact force was Polach, the model can be used for derailment simulation analysis. Calculation results, Vampires software simulation results and the measured results were compared. It was pointed out that the wheelset in the condition of asymmetric braking force, compared to the shaft, guide wheelset have greater risk, a great braking torque can cause the wheel to coast and oscillate laterally.

Suda et al. [22] studied the dynamic behavior of rail vehicles during curve negotiation when traction or brake torque was applied, and performed computer simulations using full car body models, in which considered non-linear characteristics of the contact force between wheel and rail, as shown in Fig. 3. It was proved that wheel lateral displacement was considerably smaller and wheel attack angle was almost zero within wide range of torque when under the same curve conditions. Yao et al. [23] proposed an innovative structure for a heavy haul coupler with an arc surface contact and restoring bump stop. In order to verify and simulate the process of emergency braking, a multi-body dynamics model was established, which four heavy haul locomotives and three detailed couplers were contained. The study pointed out that the combined contact couplers were suitable for heavy haul train and have good dynamic performance.

In addition, some scholars began to study the safety when train through turnout. Belforte et al. [24] established a train longitudinal dynamics analysis model TSDYN, the lumped parameter method was adopted to construct the mathematical
model of the air brake system, the working state of the buffer were described in detail, based on this, coupling force of the train under braking condition was studied, and the results were input to the three-dimensional dynamic model to analyze the train's running safety, the research pointed out that emergency braking in the turnout section posed a greater threat to the derailment of the vehicle. Pugi and Rindi et al. [25] according to the characteristics of the Italian railway train braking equipment, divided train marshaling into three types of marshaling, PP, GP and LL. Train longitudinal dynamics model was established, and calibrated by using the experimental data of model, the differences between the three schemes were analyzed, the mixture train model of the single degree of freedom and whole train was established by ADAMS software, the train derailment safety of turnout area was studied. Zhao et al. [26] analyzed the safety of slave control locomotive under braking conditions, analysis method was firstly adopted longitudinal dynamics simulation software to get coupling force according to the specific working conditions, after that, coupler force exerting on the locomotive, the locomotive including two carriages, locomotive coupling model between each carriage was established, the results showed that due to locomotive’s braking time delay, coupling free pendulum angle have bigger influence on the safety of locomotive.

After studying the effect of braking conditions on the curve passing performance of the three freight bogies, Berghuvud [27] pointed out that the braking force can improve the curve passing performance of the traditional three-Piece bogie, while deteriorate the curve passing performance of cross-connect bogie. Wilson et al. [28] discussed the criteria for judging the safety of vehicle wheel/rail operations during train braking, and pointed out that the large coupler-pressing force caused by emergence braking may lead to partial wheel load reduction, the force can also lead to the wheel and rail interface to produce large lateral force and derailment coefficient, this situation needed to be evaluated in particular, Russia and the CIS national security assessment standards specifically provided regulations for this. Yang et al. [29] used SIMPACK to establish a train mixing model, in which the locomotive was described in a three-dimensional dynamic model, and others vehicles were described in a single-mass model, the curve passing performance of the train under the braking condition was studied. To investigate the effect of braking/traction torque to the longitudinal and lateral dynamics of wagons, Zhang et al. [30] developed a wagon system model, as shown in Fig. 4. Sensitivity of wagon dynamics to braking severity was illustrated through numerical examples.

Figure 1. Heavy-haul train–track coupled dynamic model (side view) [14]

Figure 2. A wheelset within a bogie frame [20]
4. Conclusions

At present, relating dynamic analysis software such as SIMPACK, UM, provide the wheel/rail dynamics analysis module, the software have multi-carriage of the vehicle dynamics modeling and analysis function, have been able to
complete the conventional locomotive vehicle dynamics calculation. Especially the UM software, provides a special train module [31,32], and a great convenience for the 3D train dynamics modeling.

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