Recent Research and Development on Numerical Simulation Techniques in Railway Dynamics

Fumiaki UEHAN
Railway Dynamics division

Railways are composed of overhead contact lines, vehicles, tracks and structures, and display a complex dynamic behavior as a result of interactions between these components. The Railway Dynamics Division of RTRI covers all areas related to the dynamic aspects of these railway components, and carries out R&D aimed at improving the safety and maintainability of the railways. The main mission of this division, is to develop railway simulators using advanced numerical simulation techniques and high performance computing. This paper introduces the latest R&D on numerical simulation techniques in railway dynamics.

Keywords: railway dynamics, simulation, interaction, coupled analysis, contact phenomena

1. Introduction

A railway system is a dynamically complex network of structures, tracks, vehicles, overhead contact lines and other components where “railway dynamics” phenomena, in which interaction between moving vehicles and facilities on the ground plays an essential part, occur. Dynamic interaction between pantographs and overhead contact lines, between rails and wheels, between structures and tracks and vehicles, between vehicles and the surrounding environmental elements such as air and water (rain and snow) and between other components can affect the safety, maintainability, environmental harmony and other attributes of the railways (Fig. 1). The Railway Dynamics Division of RTRI, where this paper originated, has been working on the development of a “railway simulator” capable of reproducing these dynamic phenomena in cyberspace.

The Division has been endeavoring to clarify complex phenomena in which dynamic interaction plays an essential part through the development, application and coupling of various numerical analysis methods. This paper presents an overview of some of the recent studies on numerical simulation techniques in railway dynamics.

2. Simulation of overhead contact lines and pantographs

Efforts are underway to develop an overhead line/pantograph simulator as a tool to support the design/development of pantographs and contact lines as well as help identify the causes of accidents involving overhead contact lines and pantographs. When completed, the simulator, which uses three-dimensional finite element models of overhead contact lines and pantographs to calculate the contact between those components, should be capable of reproducing their behaviors in crossings and curved sections, which currently is difficult to examine in detail. Along with this, efforts have also been made to develop techniques to couple the simulator described above with a vehicle vibration and tunnel air-flow simulator (average flow velocity around the pantograph).

With regard to the overhead contact line model, wires and fittings, such as droppers and pull-off arms, are modeled as beams and each node is given six degrees of freedom to enable the reproduction of behavior in curved sections as well as of static geometry changes due to temperature. With regard to pantograph modeling, a three-dimensional dynamic model has thus far been developed that is capable of reproducing vibrations with relatively small amplitudes (Fig. 2) [1].

Currently, a contact analysis method combining three-dimensional models of overhead contact lines and pantographs is being developed.
3. Coupled analysis of vehicles, tracks and structures

3.1 Wheel-rail rolling contact simulation

The wheel-rail rolling contact simulator is designed to run a structural analysis program which, by means of elastic and elasto-plastic analyses based on the three-dimensional finite element method, calculates in real time unsteady impact behavior (force, stress, acceleration, etc.) generated between the wheel and rail, and its subsequent transmission. To study the nonlinearity of materials (such as reduction in yield stress) resulting from the wheels becoming hotter from braking, an algorithm was developed that combines a thermal conduction analysis feature, which takes into account thermal conduction, heat transmission, and heat generation from radiation and friction with a structural analysis feature. Currently the algorithm is being verified using a simple analytical model simulating wheels and rollers on a test bench. With regard to the elasto-plastic analysis, confirmation was obtained that the technique was capable of factoring in both thermal stress (the green area in Fig. 3 (b)) generated as the wheel becomes hotter during braking (Fig. 3 (a)) and plastic deformation caused by strong wheel-rail contact force (the red area in Fig. 3 (b)). Currently, using a detailed shape model of the wheels and rollers on the test bench, quantitative comparisons with test results and verifications are underway with respect to braking time, the increase in temperature and other parameters.

3.2 Simulation of dynamic behavior of ballasted tracks

Ballasted tracks require continuous attention and maintenance as the ballast deteriorates through wear, rotation, movement, etc. under the dynamic load of passing trains. RTRI has been conducting research and development to clarify the deterioration mechanisms under shock loading and long-term settlement with a view to finding effective solutions. The distinct element method is considered effective in analyzing the dynamic behavior of individual ballast stones as the technique models the ballast as granular material. However, the method models the ballast as a rigid body and, as such, cannot handle the transmission of shock load waves, which is a cause of degradation, or natural vibration of the track structure. Given these limits, RTRI in association with the Japan Agency for Marine-Earth Science and Technology developed a ballasted track simulator, which is based on a distinct element method for the analysis of elastic material (QDEM), capable of analyzing ballast as granular material while factoring in the viscoelasticity of individual ballast stones [2].

Figure 4 shows displacement of a ballasted track obtained from a one-way coupled analysis in which the dynamic load of a passing train is calculated using a wheel-rail elasto-plastic dynamic rolling contact simulator and the calculation is input into a ballasted track QDEM model. While the conventional distinct element method assumes that ballast is moved sideways, the coupled analysis found that the train’s driving torque pushes ballast down in the trailing direction while at the same time the passing axle load subjects the sleepers to first order bending deformation, resulting in the ballast’s deformation concentrating in and around the center of the sleepers. The findings point to the fact that in track maintenance, the ballast immediately below the sleepers is removed based on experience, a technique called “inner hollowing.”

3.3 Simulation of vehicle behavior following a derailment

To enable the analysis of vehicle behavior following an earthquake-induced derailment, an efficient analysis method for post-derailment vehicle behavior was developed that focuses on post-derailment contact between vehicle components (car body, bogie and wheelset) and ground facilities (track and other structures), by improving the dynamic vehicle-structure interaction analysis program DIASTARS III [3] developed by RTRI [4].

Figure 5 shows the concept of the post-derailment ve-
Vehicle behavior analysis method. With the method, contact judgments are made with respect to a limited number of pairs of a contact point C on the vehicle and a contact surface Γ on the ground facilities, selected from numerous possible contact points, achieving the computation time that is about a hundredth of the time taken by general-purpose FEM software. The method has been improved in that contact points on the vehicle can be set on all of the car body, bogie and wheelset.

Figure 6 shows an example of results of the post-derailing vehicle behavior analysis method with respect to the contact between the bogie and track structure. The data in the example was obtained when a vehicle running at 300 km/h on a rigid track was subjected to an input of a 5-period sine wave with a maximum acceleration of 3.8 m/s² and a vibration frequency of 1 Hz and derailed, causing a protrusion on the front bogie to hit track structures along the rails. The figure shows that the vehicle derailed about four seconds after the input and that the contact point C on the bogie hit the contact surfaces Γ and did not go any further, which prevented derailment. This indicates that the method can also be used for verifying the effectiveness of vehicle guide devices installed on wheelsets and bogies. The method is also capable of evaluating the contact force between a contact point C and a contact surface Γ, and therefore could be used for determining the design load on vehicle guide devices.

4. Simulation of air and snow around a vehicle

4.1 Simulation of air flows

An air flow simulator [5], fluid analysis software based on the Cartesian grid method, developed by RTRI was enhanced to include the capacity to simulate rail movement and wheelset rolling while the train is running. The simulator is capable of reproducing conditions that more accurately reflect actual conditions than the conventional train running simulation that only factors in the moving belt, raising expectations for more accurate simulation of flow fields around the bogie. The analysis method was applied to a running bogie model (Fig. 7) to evaluate the impact of wheelset rolling. It was observed that wheel rotation induced flows around the vehicle (Fig. 8).

4.2 Simulation of snow accretion

When vehicles run along a snow-covered track, the snow is lifted and accretes under the vehicles’ floors and on the bogies. Accreted snow can become nearly as hard as ice, and the hardened snow can fall as the vehicles vibrate while running or when shaken as the vehicles pass turnouts onto the ballast, possibly causing the ballast stones to fly and damage the vehicles, ground facilities and adjacent buildings and homes. Accreted snow can also become wedged between the rails of a turnout, possibly preventing the turnout from switching properly.

As a solution to this problem, a snow accretion analysis method was developed capable of reproducing the snow accretion process, as illustrated in Fig. 9, with the aim of helping to develop railway vehicle shapes resistant to snow accretion.

With the envisioned method, firstly air flow calculations are made using an air flow simulator. In the second step, snow is modeled as spherical elements and the tracks of flying spherical elements are calculated using the velocity distribution of air flows. In a further step, snow accre-
tion calculations are made using a particle simulator. The shapes that have changed with snow accretion are reflected on the boundary shapes for the air flow simulator. In summary, the tracks of snow particles based on air flow calculation dictate the snow accretion calculation and the change in boundary shapes based on the snow accretion calculation dictates the air flow calculation. This two-way coupled calculation constitutes the snow accretion analysis method.

Figure 10 (a) shows the results of snow accretion analysis on a railway vehicle model simulating a wind tunnel test using artificial snow particles. The opaque white areas indicate accreted snow particles while the semitransparent white areas indicate flying snow particles. The lines are flows and the various colors indicate corresponding velocities. Figure 10 (b) shows the results of a snow accretion experiment on a bogie model conducted using a wind tunnel and artificial snow particles, seen from below. The snow accretion near the downwind closing plate and other areas in the snow accretion experiment and analysis resemble each other. In addition, Figure 10 (a) shows that the flows that have entered from around the upwind closing plate tend to stagnate near the downwind closing plate. The above suggests that, once the relationship between snow flows and accretion is clarified through snow accretion analysis, it is then possible to start searching for effective measures to limit snow accretion by altering the vehicle geometry.

5. Conclusion

This paper presented an overview of simulation techniques and examples of analyses relating to the field of railway dynamics where various dynamic phenomena are induced through interaction between railway system components. The Railway Dynamics Division will continue to work on the development and application of new simulation techniques, build an integrated environment that promotes effective coupling of those techniques for analysis, and develop simulators that help clarify phenomena for enhanced railway safety, lower maintenance cost, greater harmony with the environment and other benefits.

References

[1] Nagao, K., Koyama, T., Ikeda, M., “Parameter Identification of the Three-Dimensional Pantograph Simulation Model based on Vibration Test of the Actual Pan- tograph,” J-Rail 2018, SS8-1309, 2018 (in Japanese).
[2] Nishiura, D., Sakai, H., Aikawa, A., Tsuzuki, S., Sakaguchi, H., “Novel discrete element modeling coupled with finite element method for investigating ballasted railway track dynamics,” Computers and Geotechnics, Elsevier, 2017.
[3] Wakui, H., Matsumoto, N., Matsuura, A., Tanabe, M., “Dynamic Interaction Analysis for Railway Vehicles and Structures,” Proceedings of JSCE, 513/1-31, pp.129-138, 1995.
[4] Goto, K., Sogabe, M., Tanabe, M., Watanabe, T., Tokunaga, M., “A Simple Analysis Model for Contact between Wheelset Members and Track Structures Using MBD,” RTRI REPORT, Vol.31, No.4, pp.41-46, 2017.
[5] Nakade, K., Noguchi, Y., Kikuchi, K., “Fluctuating aerodynamic force on railway vehicle under crosswind using large-eddy simulation,” presented at International Colloquium on Bluff Body Aerodynamics and Applications, Boston, USA, 2016.

Author

Fumiaki UEHAN, Dr. Eng.
Director, Head of Railway Dynamics Division Research Areas: Structural Mechanics, Measurement Engineering