Recent Trends in Research into Numerical Simulation Techniques for Railway System Dynamics

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RTRI has been working on innovative technical solutions for various dynamic problems caused by characteristics of the railway system. Numerical simulation techniques are one of the powerful tools which can be used to promote this kind of research; therefore, RTRI started development in 2010 on a simulation tool called the "Railway Simulator" using high performance computing technologies. This paper describes recent trends in research into numerical simulation techniques applied to research on dynamics in the railway system.

Keywords: dynamics of the railway system, dynamics, simulation

1. Introduction

Today, numerical simulation is indispensable in advancing research in natural science, with computational science having come to be regarded as the third branch of science after theoretical and experimental sciences. Contrary to theoretical and experimental sciences, the performance of computational science, or computing performance, has been improving rapidly, with computers becoming about 10 time faster in three years and about a thousand times faster in ten years. Improvement in computing performance leads directly to higher computation accuracy and expansion of the scope of phenomena that can be analyzed. In other words, this results in the rapid extension of areas to which numerical simulation can be applied.

Conscious of this situation, RTRI made simulation technology development as one of its highest priorities for basic research in the former Master Plan "RESEARCH 2010" which ran until the end of FY2014, and promoted the development and improvement of simulation techniques. The sophistication of simulation technology is also promoted as a high priority theme for basic research in the current Master Plan "RESEARCH 2020" launched in 2015. A central part of RTRI work in this regard has been the development of the "Railway Simulator" (Fig. 1) since 2010 which enables the numerical simulation of multiple phenomena related to train operation and also the coupling of different simulations [1].

This paper introduces in a little more detail current research trends in numerical simulation of railway system dynamics.

2. Simulation of phenomena which are difficult to observe

One of the benefits of numerical simulation is phenomena which are usually difficult to analyze theoretically or difficult to observe in experiments can be numerically reproduced. if the governing formulae of the related system can be derived. This Chapter describes examples of this kind of simulation being achieved.

Fig. 1 Outline of Railway Simulator
2.1 Analysis of the dynamic rolling contact between wheels and rails

Railway vehicles are sustained, guided laterally and given driving force for acceleration and deceleration by the contact forces acting between wheels and rails. The contact force acts on a small contact area generally called the ‘contact patch.’ Because the diameter of a contact patch is only slightly more than ten millimeters, the stress applied to the wheel and rail by the contact force locally, exceeds the steel’s yield stress even when the vehicle is stationary, causing plastic deformation under these points. In addition, wheels rotate on the rails with slight slippage which transmits the driving force to the wheels. These contact force characteristics acting on the contact patch not only influence the running safety of vehicles but also lead directly to wear and fatigue on the top surface of the rail and wheel tread. It is therefore extremely important to closely monitor the rolling contact between wheels and rails.

Theoretical considerations of rolling contact between wheels and rails were approached by Carter and Kalker [2]. These proposals, however, were based on the elasticity (linear) theory and as such cannot explain the influence of plastic deformation. Meanwhile, trials to measure the shape of contact patches on rotating wheels using ultrasonic sensors have been under way [3]. However, that method is capable of measuring only when the wheels are rotating at low speeds and is unable to produce quantitative measurements of the stress distribution. As described above, the rolling contact between wheels and rails is a complex phenomenon and is difficult to observe, consequently numerical analysis is an effective way to study rolling contact. A computation program CONTACT developed by Kalker is a typical example of this [2] and has been used in many studies. However, as it is based on boundary element methods, it is weak in handling the nonlinearity of materials. Furthermore, it cannot handle the behavior of wheel as they roll over discontinued sections, such as rail joints.

To overcome these constraints, RTRI has been developing a Wheel-Rail Rolling Contact Simulator [4, 5] jointly with Professor Okuda of the University of Tokyo. This numerical simulation tool is not only capable of handling the nonlinearity of materials and the geometric nonlinearity more accurately but also capable of analyzing the dynamic rolling contact. This simulator, based on a large-scale, parallel-finite-element, structural analysis software FrontISTR, is capable of analyzing dynamic rolling contact behavior without presupposing any other contact models by dividing the top surface of the rail and wheel tread into uniform, fine meshes and analyzing the stress distribution on the contact patch with sufficient resolution. To prevent expansion of the calculation scale due to the adoption of a uniform fine mesh, a method called “caterpillar mesh” (Fig. 2 (a)) was developed. This method constructs the rail model by connecting a series of rail model units of the same length in continuous succession from the trailing edge to the leading edge with constant timing. In addition, this simulator combines the on-memory area division function which distributes the contact pairs of the finite-element wheel and rail to the same memory area. The distribution of stress on the rail and the distribution of contact force in the tangential direction on the contact patch under the rolling wheel calculated using this simulator are shown in Fig. 2 (b) and Fig. 2 (c), respectively. With wheels in a quasi-static rolling state at low train running speed, it was observed that the distribution of stress on the contact patch nearly agrees with the corresponding results from Kalker’s CONTACT program. In the future, analysis of dynamic rolling contact at high train running speed is planned for verification of the simulator’s performance in that area. Furthermore, there are plans to enable the simulator to analyze rolling contact in curved sections.

RTRI has also been working on the development of a simulator capable of computing the behavior of a film of water between the wheel and the rail based on the SPH method, a particle method. The SPH method considers a continuum as an assembly of particles and expresses the physical quantity of a continuum as the aggregate of the physical quantities of the individual particle components. With these properties, the SPH method is suitable for computing the behavior of free fluid surfaces such as films of water that change in shape freely. By combining this simulator with the Wheel-Rail Rolling Contact Simulator, it is possible to analyze the behavior of a film of water on the top surface of a rail when a wheel is rolling on a wet rail.
surface (Fig. 3). Currently, the model for the film of water is two-dimensional and therefore the behavior of the actual water film cannot be reproduced. RTRI is therefore planning to upgrade this simulator to enable handling of three-dimensional models.

2.2 Dynamic analysis of the behavior of ballasted tracks based on discrete element method

Ballasted tracks are widely used, mostly on conventional lines because of the ease of construction, excellent drainage, low cost and ease of repair. On the other hand, subjected to repetitive loads from passing trains, which typically causes settlement and other deterioration over time, ballasted tracks require regular maintenance to maintain them in good condition. As track maintenance is labor and cost intensive, there have been studies and development projects to understand the mechanisms underlying long-term deterioration of tracks and to propose effective countermeasures, and these efforts have produced many useful results. However, the dynamic behavior of ballasted tracks has not been fully clarified yet because it is difficult to fully observe the dynamic behavior of individual crushed stones forming the ballast.

Simulation using a discrete element method is suitable for analyzing granular materials like ballast. Based on that, RTRI has been developing numerical simulation tools that use a discrete element method to reproduce the dynamic behavior of individual crushed stones forming the ballast. Figure 4 (a) shows an example of the calculated displacement of ballast around the rail joints using DEMCS-track, a discrete ballasted track model developed jointly with Professor Matsushima of the University of Tsukuba [6]. This model uses a layer of individual crushed ballast stones as a discrete element (ballast element made of rigid-jointed spheres), enabling the movement of individual crushed stone to be reproduced by computation. With this model, it is possible to grasp firsthand the structural change (settlement and flow) in ballast layers due to passing trains. Ballast elements used in DEMCS-track are created based on shape measurements of actual crushed stones to reflect real data in the model. This method uses an assembly of rigid spheres as a ballast model, requiring less computation than in a quadruple discrete element method (QDEM) described below, and therefore this tool has been used for the evaluation of the effects of a range of proposed solutions such as elastic track design.

In parallel, RTRI has been involved in joint research with the Japan Agency for Marine-Earth Science and Technology, to develop a Ballasted Track Simulator that employs QDEM capable of analyzing granular materials while considering the viscoelasticity of each grain element [7, 8]. Because this simulator is capable of reproducing the behavior of crushed stones as a continuum, it can analyze the stress distribution within the ballast layer as well as the load transmission due to the elastoplasticity of crushed stones. Because of the heavy computation load it requires, the simulator employs a parallel algorithm using GPUs (graphics processing units) for computation. Figure 4 (b) shows an example of the behavior analysis of a four-sleeper segment of ballasted track under passing trains. This example shows the computed settlement of a ballasted track segment soon after tamping under the sleepers. In this example, the characteristics of the initial settlement are clearly reproduced.

Our future plans include not only expanding the scope of ballasted track models (in the longitudinal direction along the rails) that can be handled by these analysis tools but also the analysis of dynamic ballast behavior in special rail conditions such as around rail joints by combining this tool with the Wheel-Rail Rolling Contact Simulator described earlier in this paper.
3. Simulation of phenomena that are difficult to reproduce in experiments

Another benefit of numerical simulation is that it can reproduce events that are difficult to reproduce experimentally or that can be reproduced in experiments but cannot be reproduced more than once due to cost and other practical reasons, such as derailment and collision. As an example of the type of phenomena in question, this paper introduces the numerical simulation of the dynamic behavior of railway vehicles and structures during derailment caused by a major earthquake.

Understanding how vehicles and structures behave in a major earthquake is important for evaluating the performance of derailment prevention devices and the seismic performance of structures. While experiments have been conducted using scale models to reproduce vehicle derailment, it is difficult to reproduce these events identically. As such numerical simulations have been conducted in parallel with experiments [9]. Detailed research has thus been carried out into the derailment behavior of vehicles in a major earthquake utilizing numerical simulation.

Figure 5 (a) shows an example of analysis which calculates the damage occurrence rate in an earthquake along an entire railway line through simulation [10]. This simulation was performed using a dynamic vehicle-structure interaction analysis program DIASTARS III developed by RTRI. To reproduce a vehicle running along a continuous railway structure, the structure was divided into analysis sections with quasi-borders, while the dynamic behavior of running vehicles on these separate sections during an earthquake was calculated through parallel computation. These calculations were used to obtain derailment occurrence rates. By conducting a large number of analyses using this tool, it was possible to evaluate the effect of various parameters, such as specifications of vehicle and structure, train speed, types of seismic ground motion and the direction of seismic source, on possible earthquake damage to vehicles.

Figure 5 (b) shows an example of the evaluation of vehicle behavior in case of derailment during a major earthquake taking vehicle/structure contact into consideration. This analysis used a modified version of DIASTARS III which allows vehicle-structure contact behavior evaluation. Specifically, acting forces generated at contact detection points arranged on a multibody vehicle model and nodes arranged on a finite element structure model were calculated using the penalty method. Because it is not easy to reproduce the extreme phenomena of a major earthquake in experiments, nor is it easy to accurately measure the acting forces generated by vehicle-structure contact, this program is expected to become a useful tool for evaluating derailment prevention measures, etc.

4. Conclusion

This paper introduces current RTRI research trends in

![Diagram](a) Evaluation result of the possibilities of damage to vehicles along an entire railway line in an earthquake

![Diagram](b) Evaluation of vehicle behavior in an earthquake taking vehicle-structure contacts into consideration

Fig. 5 Analysis of dynamic behavior of vehicles and structures in an earthquake
Numerical simulation of railway system dynamics. Numerical simulation is expected to play a greater role in future research and development projects. RTRI will continue to maintain its drive to develop numerical simulation with higher reliability and more sophisticated functions.

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