Wanming Zhai

Vehicle–Track Coupled Dynamics

Theory and Applications

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Preface

Dynamic interaction between train and track is increasingly intensive with the rapid development of high-speed railways, heavy-haul railways, and urban rail transits, causing more critical and complex vibration problems. Higher train running speed would result in severer train and track interaction, bringing more prominent problems in terms of running safety and stability of the train moving on elastic railway track structures. It must ensure that the train has a good ride comfort when running at a high speed without overturn or derailment. Additionally, the greater the wheel–axle load of a vehicle, the stronger the dynamic effect of the vehicle on track structures, inducing more serious dynamic damage to railway tracks. This requires mitigation of the dynamic interaction between heavy-haul train and track. Obviously, seeking solutions to the abovementioned sophisticated dynamic interaction problems of the large-scale system just from the vehicle system or the track system itself is no longer sufficient. It is necessary to conduct dedicated and in-depth research on the dynamic interaction between rolling stock and track systems. Only with a deep and comprehensive understanding of the mechanism of vehicle–track dynamic interaction is it possible to implement reasonable approaches to minimize the dynamic wheel–rail interaction, to obtain optimal integrated designs of modern rolling stocks and track structures, and eventually to ensure safe, smooth, and efficient train operations. Owing to the fast development of computation technologies, it is realistic today to study and simulate such coupled dynamics problems by considering the vehicle system and track system as a large integrated system with interaction and interdependence. This is the original intention of the vehicle–track coupled dynamics theory discussed in this book.

The author proposed the concept of *Vehicle–Track Coupled Dynamics* for the first time in the late 1980s. In 1991, the author completed his doctoral thesis entitled *Vertical Vehicle–Track Coupled Dynamics*. In 1993, a research paper for investigating the vertical interaction between vehicle and track based on the vehicle–track coupled dynamics was published at the 13th Symposium of the International Association for Vehicle System Dynamics (IAVSD), and then was included in a supplement of the IAVSD journal *Vehicle System Dynamics (VSD)* in 1994. With the continuous funding from the National Natural Science Foundation of China

(NSFC), the National Outstanding Young Scientist Foundation of China (received by the author in 1995), the Ministry of Science and Technology of China (MOST), the China Railway (former China Ministry of Railway), railway industry companies, and others, the research group (including graduate students) led by the author carried out many follow-up research tasks, and published the first academic monograph in this research field entitled *Vehicle–Track Coupled Dynamics* (First edition, in Chinese) in 1997. Afterward, the second, third, and fourth editions of the monograph (in Chinese) were published in 2002, 2007, and 2015 respectively, which became the most fundamental reference books in the field of railway system dynamics and design of rolling stocks and track structures in China, especially for high-speed railways.

In recent years, with the great-leap-forward development of modern railway transportation, especially for high-speed railways, the vehicle–track coupled dynamics theory needs to address more demanding engineering requirements and many new emerging open problems. Supported by the NSFC Major Project (Grand No. 11790280), the NSFC Key Project (Grand No. 51735012), the Program of Introducing Talents of Discipline to Universities (111 Project) (Grant No. B16041) from the China Ministry of Education (MOE), the author led his group to extend the vehicle–track coupled dynamics theory through more elaborate theoretical analysis and more extensive investigations of field problems uncovered in practice. Meanwhile, worldwide research on this topic has also been extremely active and achieved much progress recently. The first English monograph re-edited from the author's Chinese monographs is published when the relevant field is undergoing rapid development in terms of theoretical research and engineering practices.

The writing of this book would not be possible without the support from various individuals and organizations. First, the author is most grateful for the continuous support from the NSFC, the MOST, the China Railway, the MOE, etc. during the past decades. The author also owes much gratitude to those who have participated in the amendment of this English monograph. They are Dr. Shengyang Zhu, Dr. Liang Ling, and Dr. Zaigang Chen from the author's group; Dr. Yunshi Zhao, Dr. Xiaoyun Liu, and Dr. Ilaria Grossoni from University of Huddersfield (UK), Dr. Guoying Tian from Xihua University (China). The author would like to thank the following scholars with special gratitude: Dr. Qing Wu and Dr. Tim Mcsweeney from Central Queensland University (Australia), Prof. Zili Li from Delft University of Technology (the Netherlands), Prof. Kelvin C. P. Wang from Oklahoma State University (USA), and Prof. Manicka Dhanasekar from Queensland University of Technology (Australia), for their extreme enthusiasm in proofreading this book. Some calculation examples performed by Dr. Liang Ling are also gratefully acknowledged. Finally, the author wants to thank his Ph.D. students, Mr. Yu Sun, Ms. Yu Guo, Mr. Jun Luo, Mr. Tao Zhang, and Ms. Mei Chen, for their assistance in carefully editing and supplying photographs, diagrams, and relevant information.

The author believes the publication of this English monograph on *Vehicle–Track Coupled Dynamics* will be conducive to both the investigation of railway engineering dynamics and the development of modern railway industry.

Chengdu, China Wanming Zhai
December 2018

Contents

Chapter 1
Introduction

Abstract To better understand vehicle–track coupled dynamics which is a new theoretical system, it is necessary for readers to understand the following questions. What is the background under which the theory was proposed? What is the academic rationale of the theory? What are the research scopes and research methodologies? In this chapter, the author will give detailed explanations of these questions.

1.1 Background of Vehicle–Track Coupled Dynamics

Railways are major transportation arteries in many countries and play a very important role in social and economic development. The railway transportation system is a type of wheel–rail contact transportation system (“wheel–rail system” for short). Rolling stocks (including locomotives, passenger cars, and freight wagons, all referred to as “vehicles” in this book) and tracks are essential components of the railway system. The function of wheel–rail transportation is achieved via the interaction between wheels and rails. Wheel–rail interaction is the most significant feature that distinguishes the railway system from other types of transportation systems.

For a long time, studies on railway vehicle dynamics and track structure vibration were carried out separately. This resulted in two relatively independent disciplines, i.e., vehicle dynamics [1, 2] and track dynamics [3, 4].

In classic vehicle dynamics [1, 2], the vehicle system is the research object while the track structure is considered as a “rigid support foundation” (i.e., a rigidly fixed boundary), neglecting the dynamic influence of track vibrations on the vehicle system. Under this situation, geometric irregularities of the rail surface are treated as external disturbances of the vehicle system. In this research field, the dynamic behaviors of the vehicle, including the hunting stability, the running safety, the ride comfort, etc. are investigated with the assumption that the vehicle operates on a rigid rail surface. A basic model illustrating this is shown in Fig. 1.1.

In classic track dynamics [3, 4], the vehicle is usually simplified as external excitation loads $Pe^{i\omega t}$ for the track system (the harmonic vehicle loads P are applied

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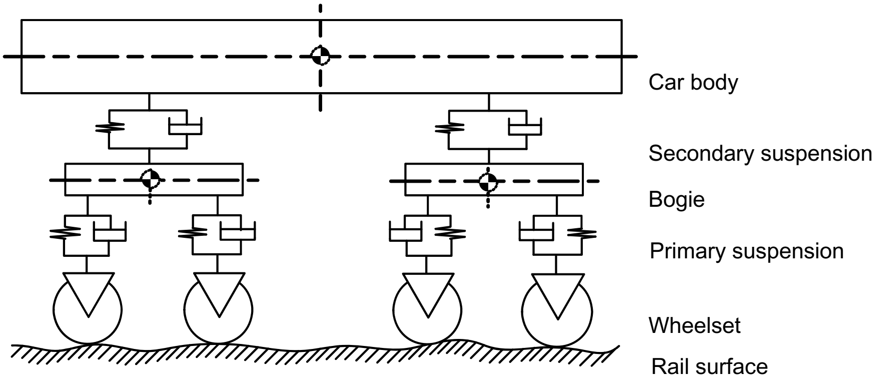

Fig. 1.1 Classic vehicle dynamics model

on fixed points of the track system, or applied as moving loads on the track at a speed of v). The characteristics of the vibration response and deformation of the track structure are analyzed correspondingly. The fundamental model of the classic track dynamics is shown in Fig. 1.2.

Thanks to the long-term studies and practices by railway scientists all over the world, the theories of vehicle dynamics and track dynamics are becoming more and more complete. Significant achievements of these systematic studies have been reported from many fields, including vehicle dynamics modeling, wheel–rail contact geometry, wheel–rail creep theory, vehicle hunting stability, curve negotiation performance, track dynamics modeling, vibration characteristics of track structure, track loading, and deformation characteristics, etc. These research outputs have laid the theoretical foundation in revealing and understanding vehicle dynamics performances and track dynamics characteristics. These outputs have also played a magnificent role in the development of the railway transportation systems.

The rapid development of modern railway transportation, especially the dramatic increases of operating speed, hauling mass, and transportation density, makes the

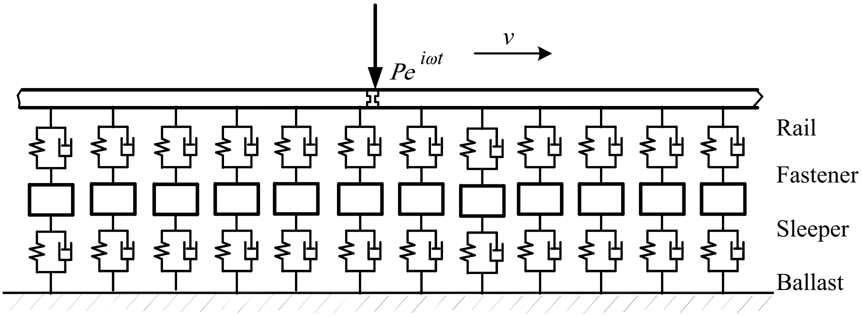

Fig. 1.2 Classic track dynamics model

dynamics problems of the railway vehicle and track systems more prominent and complicated. In general, the higher the operating speed of the train, the stronger the dynamic interaction between the vehicle and the track, the more prominent the problems of running safety and ride comfort. For one thing, it must be guaranteed that the train passes key railway sections (including horizontal curves, vertical curves, switches, turnouts, bridge approach transitions, etc.) safely at a reasonably fast speed or even at a high speed without overturn and derailment. In addition, it must be ensured that the rolling stock can operate with a good ride quality and comfort under the disturbance of track irregularities. Normally, the heavier the gross mass of the vehicle, the stronger is the dynamic interaction between wheel and rail, and the more detrimental are the dynamic effect of the vehicle on the railway infrastructure. Therefore, it is critical to significantly alleviate wheel–rail dynamic interaction by exploring efficient and economical solutions.

Here, we can take the Chinese railway as an example to illustrate this issue. Chinese railway transportation has been in a highly loaded situation for a long time. On the one hand, the railway network density is geographically relatively low, however, the total transport volume is very large. This situation results in a very high traffic density which ranks first in the world. At present, the Chinese railway is able to complete one-fourth of the transport volume of the world's railways with only 6% of the world's railway network length! On the other hand, given the need to increase operational speeds of the passenger and freight trains to satisfy the demands of rapid socioeconomic development, upgrades of existing railway lines, which were originally designed and constructed with relatively low standards have been carried out repeatedly over recent decades. From 1997 to 2007, six major speedup projects were launched and implemented, which have increased the maximum train operational speed from lower than 100 km/h to over 200 km/h. The speedups have even achieved a maximum operational speed of 250 km/h. In this way, high-speed operations were successfully achieved on those existing railway lines in China. As a result, the transportation capacity was effectively improved. However, the dynamic interaction between the rolling stock and infrastructure was seriously aggravated [5]. On the one hand, the dynamic effect of running faster trains on track structures was intensified, which directly affected the fatigue life of the infrastructure and increased the cost for maintenance and repairs. On the other hand, the track geometry deformation and the subgrade settlement of the railway lines were increased, which led to increasing detrimental effects on the dynamic behavior of running trains. In particular, the vibrations and impacts that resulted from the damaged and worn wheel–rail interface have become even more prominent, which can lead to severe safety problems of the wheel–rail system.

Therefore, it is very necessary to conduct dedicated and in-depth research on the dynamic interaction between rolling stock and track systems. Only with a deep and comprehensive understanding of the mechanism of vehicle–track dynamic interaction is it possible to achieve reasonable approaches to minimize the dynamic wheel–rail interaction, to obtain optimal integrated designs of modern rolling stocks and track structures, and eventually to ensure safety, smoothness, and efficiency of train operations. In traditional disciplines, i.e., classic vehicle dynamics and track dynamics, the vehicle–track system was divided into two relatively independent subsystems. In this circumstance, it is very difficult to use these theoretical tools to solve the dynamic interaction problem of such a complex and integrated system. Given this situation, the author proposed the new concept of "vehicle–track coupled dynamics" from the perspective of an overall integrated vehicle and track system in the late 1980s, and the theory was put into practice in the early 1990s [6–12]. In 1991, the author completed his doctoral thesis entitled "Vertical vehicle–track coupled dynamics" [6]. The basic mechanism of vehicle–track coupled dynamics was published for the first time in Chinese in 1992 [7]. In 1993, a research paper on a coupled model that was established on the basis of vehicle–track coupled dynamics for investigating the vertical interaction between vehicle and track was published at the 13th Symposium of the International Association for Vehicle System Dynamics (IAVSD). The paper was then included in a supplement of the IAVSD journal "Vehicle System Dynamics (VSD)" in 1994 [8]. In 1996, a further developed "Vertical and lateral vehicle–track coupled model" was published in VSD [9]. In 2009, the "Fundamentals of vehicle–track coupled dynamics" [11] were systematically introduced in the journal "VSD". The first academic monograph in this research field titled "Vehicle–track coupled dynamics" (First edition, in Chinese) [10] was published in 1997. The second, third and fourth editions of this monograph (in Chinese) were published in 2002, 2007, and 2015, respectively [12], which became the most fundamental reference books in the field of research on railway system dynamics and design of rolling stocks and track structures in China, especially for high-speed railways. This book is the first English monograph reedited from the author's Chinese monographs.

1.2 Academic Rationale of Vehicle–Track Coupled Dynamics

In general, the fundamental academic rationale of vehicle–track coupled dynamics is to consider the vehicle system and the track system as one interactive and integrated system coupled with the wheel–rail interaction, in which the wheel–rail interaction functions as a "link" between the two subsystems. With this approach, it is feasible to carry out comprehensive studies on the dynamic behavior of the vehicle running over an elastic and damped track structure as well as on the dynamic effect of the vehicle on the track structure, in particular on the characteristics of dynamic wheel–rail interaction.

In fact, rolling stock and track are two inseparable components of a railway transportation system. The two components constitute an integrity via the wheel–rail interaction system, as shown in Fig. 1.3. A vehicle running on the track is a complicated interactive dynamics process, involving many interactive factors from both vehicle and track aspects. For example, the geometry deformation of the track can stimulate the vibration of the vehicle system. In contrast, the propagation of the

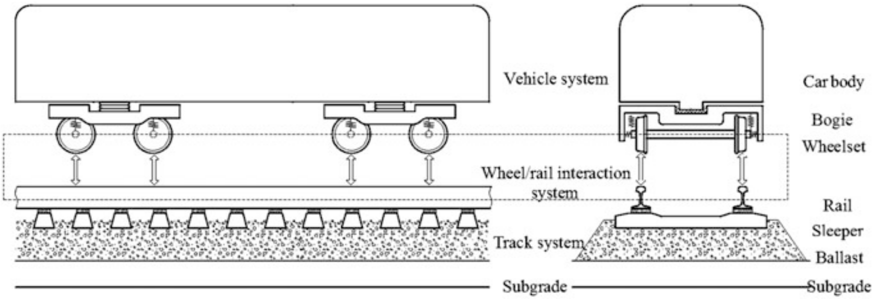

Fig. 1.3 Composition of wheel–rail system in railway transportation

vehicle vibration via the wheel–rail contact interface results in aggravated vibrations of the track structure, which in turn deteriorates the geometry condition of the track. It is evident that it is the dynamic wheel–rail contact force that significantly influences the dynamic behavior of the vehicle–track system.

Furthermore, the dynamic coupling mechanism between the vehicle system and the track system via the wheel–rail interface is illustrated in Fig. 1.4. Under the disturbance from the wheel–rail interface, the dynamic fluctuation of the wheel–rail contact force is stimulated correspondingly. The dynamic effect of the wheel–rail force can be transmitted upwards resulting in vibrations of the vehicle system. Meanwhile, the dynamic effect can also be transmitted downwards leading to vibrations of the track structure. The vibrations of wheelset and rail can directly result in dynamic variation of the wheel–rail contact geometry. Under the influence of wheelset and rail vibrations, the variation of elastic compressive deformation on the normal plane of the wheel–rail contact leads to the fluctuation of the wheel–rail normal contact force. Meanwhile, the variation of wheel–rail creepage (depending on the relative velocity between wheel and rail) in the tangential plane of the wheel–rail contact results in the fluctuation of the wheel–rail tangential creep force. The dynamic changes of the wheel–rail contact forces (wheel–rail normal force and creep force) can, in turn, affect the vibrations of the vehicle and track systems (including the vibrations of wheelset and rail). Actually, the coupled vibration of the vehicle–track system results from this interactive feedback mechanism, which ultimately determines the entire dynamic behavior of the vehicle–track system.

Obviously, the wheel–rail relationship is the essential element of the vehicle–track coupled system. The dynamic feedback between the vehicle system and track system is realized via the variations of the dynamic wheel–rail contact relationship, i.e., the dynamic wheel–rail contact deformation and contact geometry due to the vibration and deformation of wheel and rail. A typical example is given in Fig. 1.5 to clarify the influence of vehicle–track system vibrations on wheel–rail contact relationship, as well as to further demonstrate the importance of considering track system vibrations in certain problems. Figure 1.5 exhibits the dynamic variation of a wheel–rail contact point position on a wheel tread of a Chinese freight wagon negotiating a curved track with a small radius (R = 350 m). In this figure, the solid

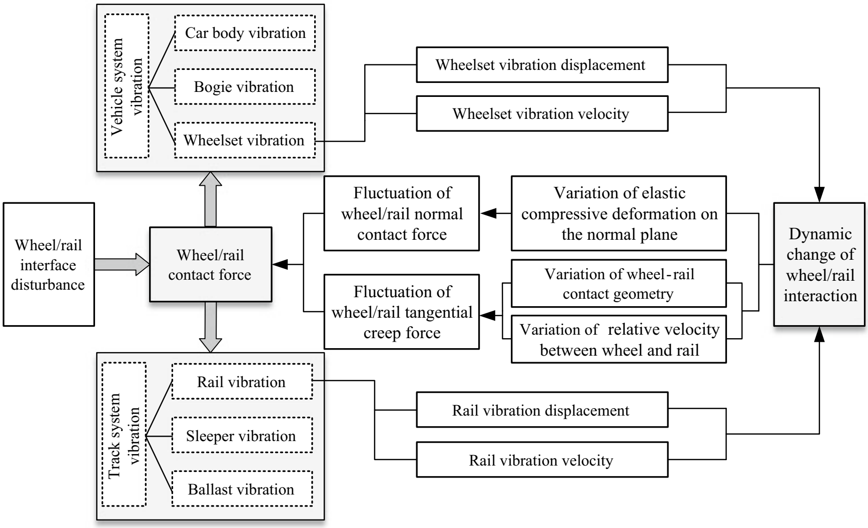

Fig. 1.4 The mechanism of dynamic vehicle–track coupled system

line is the simulation result with the consideration of track vibration effects while the dashed line is the result based on the assumption that the entire track system is remaining stationary. The results show that the contact positions are significantly different in these two cases. Noticeable changes in the position of wheel–rail contact will directly lead to dramatic variations in the magnitude and direction of the wheel–rail contact force, further affect the vibration features of the vehicle and track systems. The measured results from the Chinese railway demonstrate that the wheel–rail lateral forces can induce elastic rail displacements laterally, and then correspondingly resulting in dynamic gauge widening. For example, under a high-speed operating condition, the lateral rail displacement is about 1 mm while the track gauge is dynamically enlarged by 1–2 mm (from a high-speed test on Qinhuangdao–Shenyang passenger-dedicated line in China). Another example is from the test result on the existing Chengdu–Chongqing railway [13]. When a vehicle negotiates a small radius curve at a low speed, the lateral rail displacement and the dynamic gauge widening on a track with concrete sleepers are 1–3 mm and 2–4 mm, respectively. For the situation of timber sleepers, the corresponding rail displacement and gauge widening can even reach 6 mm and 10 mm, respectively. Obviously, for these situations where intensive vehicle–track interactions were observed, if it was assumed that the rail was absolutely stationary, the theoretical calculation result would considerably deviate from the actual situation. Therefore, the actual vibration effects of the elastic track system shall be taken into consideration in the study of the highly interactive vehicle–track system. In other words, the concept of vehicle–track coupled dynamics should be adopted.

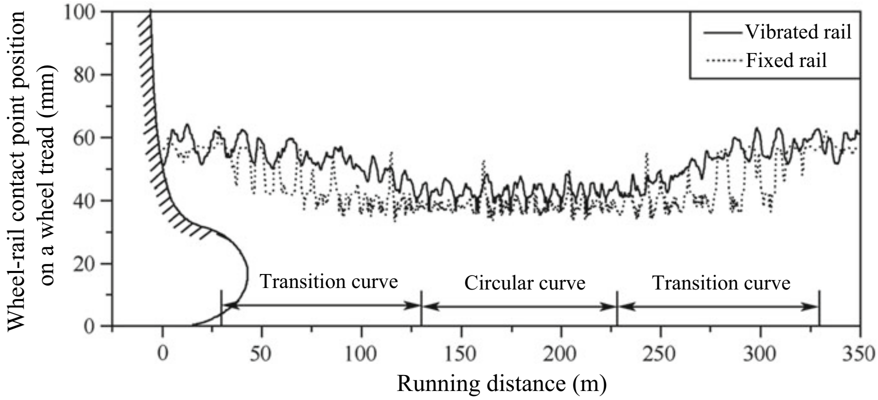

Fig. 1.5 The effect of track vibration on the dynamic wheel–rail contact geometry

Vehicle–track coupled dynamics is an interdisciplinary topic developed on the basis of classic vehicle dynamics and track dynamics. From the perspective of the discipline development, the research into vehicle–track coupled dynamics is not only necessary but also very feasible, since the theories of vehicle dynamics and track dynamics are becoming mature and the modern numerical computing techniques can also provide powerful tools for simulation analyses of such a large coupled dynamics system.

1.3 The Research Scope of Vehicle–Track Coupled Dynamics

Vehicle–track coupled dynamics involves three research aspects: vehicle dynamics, track dynamics and the wheel–rail interaction. The symbolic feature of this study is that the dynamic behaviors and interactions of the vehicle and track structure are investigated from the perspective of an overall vehicle–track system.

In general, vehicle–track coupled dynamics can be divided into three research areas: vertical, lateral, and longitudinal coupled dynamics. The vertical vehicle–track coupled dynamics is relatively independent, and can usually be studied neglecting the influence of lateral and longitudinal dynamics. However, the investigations of lateral or/and longitudinal vehicle–track coupled dynamics must be carried out considering the coupled effect of the vertical dynamics, as the vertical support system of the vehicle plays an indispensable role in the vehicle motions. In fact, the vertical, lateral, and longitudinal vehicle–track coupled dynamics are coupled interactively and are therefore inseparable from each other. They constitute a complex three-dimensional coupled dynamics system. From the perspective of the system disturbance types, vehicle–track coupled dynamics can be divided into two categories: deterministic coupled dynamics and stochastic coupled dynamics.

The vertical vehicle–track coupled dynamics is mainly related to the studies of the dynamic responses of the vehicle–track coupled system under various vertical wheel–rail disturbances and the corresponding wheel–rail vertical interaction characteristics, especially the vertical dynamic characteristics of the track affected by the vehicle. Along the vertical–longitudinal plane of the wheel–rail system, a wide variety of disturbances exist. For instance, there are local defects on the rail surface, such as squats, spalling, etc. In addition, there are cyclic irregularities, such as wavy track, rail corrugation, out-of-round wheels, polygonal wheels, and so on. Particularly, at rail joints, impulse irregularities such as hogging rails, dipped rails, large rail gaps, and weld protrusions are even more prevalent. Furthermore, defects exist in the track structure underneath the rail, such as fastener failure, voided sleepers, ballast hardening, fragmentation and voids of CA mortar underneath track slabs. Other defects include the abrupt change of the supporting stiffness at the transition of a bridge approach as well as the transition zone between different types of track structures. All these defects can cause dynamic irregularities which are related to the uneven supporting stiffness of the foundation. These dynamic irregularities can lead to vertical dynamic interactions in the wheel–rail system. The dynamic interactions at the wheel–rail interface can be transmitted upwards to the vehicle subsystems and downwards to the track subsystem. The dynamic interactions further induce coupled vibrations and impacts between the vehicle and track structure, which result in performance deterioration of the wheel–rail system in terms of safety and ride quality. These dynamic interactions also have a direct impact on the daily maintenance requirements of the vehicle–track system. In the high-speed and heavy-haul operational environment, this type of interaction will be further intensified and its hazards will become even more prominent. Under this scenario, several topics become the important issues to be solved by the application of vertical vehicle–track coupled dynamics. These are clarifying the characteristics of vertical wheel–rail dynamic interactions in different forms and their influencing factors, and seeking a mitigation strategy accordingly, such as exploring approaches to reduce vehicle's dynamic loads on the track and adopting vibration reduction techniques for the wheel–rail system.

The lateral vehicle–track coupled dynamics is basically related to the studies of the laterally coupled dynamic behaviors of the vehicle and track. More importantly, the lateral vehicle–track coupled dynamics is to be used in investigating issues of operational safety of the vehicle running on an elastic and damped track structure. First, it is critical to understand what the differences are between the analysis results when considering the elasticity and damping of the track structure and when using the traditional "rigid track" assumption in the study of the vehicle lateral stability, i.e., the hunting problem [14]. The second important topic, as described previously in Sect. 1.2, is the curve negotiation problem of the vehicle. It is inevitable that, when the vehicle negotiates the curved track, elastic lateral movements of the rail will occur and the track gauge will be transiently widened. This factor has a non-negligible influence on the dynamic contact relationship of the wheel–rail system. However, classic vehicle dynamics theory does not consider this influencing factor. Therefore, the lateral vehicle–track coupled dynamics should be utilized in the studies of the dynamic safety problems (including potential derailment) related to the elastic lateral movement of the rail during curve negotiation (especially for small radius curves). The third topic of lateral vehicle–track coupled dynamics is the safety threshold of track geometry irregularities. This is also a research topic that needs to be undertaken for improving track maintenance standards. The vertical, alignment, cross-level and gauge irregularities have important impacts on operational safety. It is very difficult to analyze these dynamic operational safety issues by investigating a single system (vehicle or track) as these problems are jointly determined by the vehicle–track interactive system. Given this situation, vehicle–track coupled dynamics can provide an appropriate theoretical platform for comprehensive studies of the safety thresholds for different types of irregularities. When multiple types of irregularities exist at the same location of the track, the problems for operational safety are even more serious and the dynamic wheel–rail interactions become more complicated. Only by the use of vehicle–track coupled dynamics, where the entire range of interactive factors have been taken into consideration, can the safety thresholds for the operational conditions of multiple irregularities be obtained. In addition, the running safety (especially for high-speed operations) of the vehicle when passing through switches and turnouts and negotiating combined horizontal and vertical curves are also within the research scope of the lateral vehicle–track coupled dynamics.

The longitudinal vehicle–track coupled dynamics is mainly related to the studies of wheel–rail stick–slip oscillation, the wheel–rail abrasion mechanism, the cause of rail corrugation, train longitudinal impact under traction/braking conditions and its interaction with the railway track, the longitudinal dynamic effect of the powertrain system on the vehicle–track system, etc. First of all, the wheel–rail system plays fundamental roles in supporting the train on the track structure vertically as well as in guiding and constraining the wheelset movement laterally. Furthermore, longitudinal wheel–rail creep also has a key role in transforming traction or braking torque into the longitudinal wheel–rail force to realize acceleration or deceleration of the train. Longitudinal wheel–rail stick–slip oscillation, wheel and rail abrasion, and rail corrugation are the main problems of the wheel–rail system during traction or braking. New breakthroughs in investigating these traditional problems are more likely to emerge if the viewpoint of the longitudinal vehicle–track coupled dynamics is adopted. Second, with the increase of train running speed and hauling mass, especially for long heavy-haul trains, longitudinal impacts between adjacent vehicles are evident when starting, braking and correcting speed. Under these circumstances, the longitudinal impacts applied on couplers are aggravated, which could lead to serious incidents such as decoupling, coupler breakage and even derailment under certain conditions [15]. In curved track sections, large coupler lateral forces can greatly exacerbate lateral dynamic interaction between vehicle and track, causing overturn or breakage of the rail. Therefore, it is an important task to explore the characteristic of the longitudinal impact in long heavy-haul trains and its effect on the track. It is also important to seek effective train handling strategies for alleviating the related problems by using longitudinal vehicle–track coupled dynamics. Third, with the rapid development of high-speed and high-powered motorized vehicles, the dynamic coupled effect of motor traction and gear transmission of the powertrain on the vehicle–track system is significantly increased [16], deteriorating the working environment of related components. In fact, heat failure of traction motor bearings, bearing cage fractures, gear tooth breakages, gearbox cracks, oil leaks, and other serious failures could occur during the operations of the vehicle. Therefore, the investigation of the dynamic mechanism of the key components in the powertrain and its coupled effect with the vehicle–track system are also within the scope of longitudinal vehicle–track coupled dynamics.

The above discussion is more related to deterministic disturbances. For nondeterministic disturbances, stochastic vehicle–track coupled dynamics is dedicated to this issue [17]. The stochastic vehicle–track coupled dynamics is mainly related to the studies regarding the vibration response characteristics and evolutionary behaviors of the vehicle–track coupled system under the excitation of stochastic track irregularities, as well as the investigation of characteristics of the vehicle system, track structure system and wheel–rail interaction in the frequency domain, and the cause of the excitation sources inducing the vehicle–track coupled vibrations (i.e., the cause of track irregularity formation). As a result, the study of stochastic vehicle–track coupled dynamics provides the feasibility to restrain and mitigate the detrimental vibrations of vehicle–track system in different situations with a targeted approach, to improve the ride quality and passenger comfort during train operations, and to reduce the fatigue damage of vehicle and track components to minimize the maintenance costs.

As a new research system distinguished from the classic theories of vehicle dynamics and track dynamics, vehicle–track coupled dynamics has a very broad application prospect in the field of railway vehicle and track system dynamics as well as in wheel–rail interaction. Over the past 20 years, the railway speedup strategy was successfully implemented in the Chinese railway and many remarkable results were achieved. Many speedup projects were carried out on existing railway lines. However, the structures of the existing lines, which were not constructed in accordance with the current high design standards, actually cannot be comprehensively upgraded in a large scale. The dynamic influences of trains on the infrastructure are greatly intensified as the operational speed increases. Therefore, the issues of how to reduce the dynamic wheel–rail interaction with an increased operational speed and how to avoid serious deformation and deterioration of the track structure in order to guarantee the operational safety have become major concerns in the Chinese railway. It is necessary to carry out systematic studies and propose appropriate corresponding countermeasures from the perspective of the overall vehicle–track system. In this regard, vehicle–track coupled dynamics has provided appropriate theoretical analysis tools [5].

High-speed and heavy-haul are the two symbolic icons in today's railway industry. However, both high-speed and heavy-haul transportation scenarios aggravate the dynamic wheel–rail interactions, which means the traditional railway systems are not well suited to these new developments. The mitigation of dynamic wheel–rail interactions has played a key role in developing modern railway transportation systems, which has contributed to economic development. In order to achieve low dynamic interactions for wheel–rail systems, optimal integrated solutions for wheel–rail systems and parameters must be sought from the perspective of system engineering where comprehensive factors of vehicle, track, and wheel–rail interface are taken into account. This aim can be achieved by the application of vehicle–track coupled dynamics theory. With detailed parameter and sensitivity analyses of the overall vehicle–track system, the basic approaches in mitigating wheel–rail interactions and the corresponding technical countermeasures can be identified. Meanwhile, the principle of optimal integrated design and the criterion of parameter selection for new types of rolling stocks and track structures can be proposed to provide theoretical guidance for the designs of high-speed and heavy-haul vehicles as well as track systems. In addition, computer simulation systems of vehicle–track coupled dynamics can be used to predict and evaluate the dynamic performance of new or existing designs of vehicle or track. In this case, simulation systems can provide a critical technical platform to evaluate the safety issues of high-speed railway design and reconstruction for existing railway speedup projects. The simulation systems can also be used to optimize vehicle design to achieve better dynamic performance. They can also be used for the analysis of rolling stock overturn, derailment and other major accidents, especially for the study of derailments caused by the wheel–rail interaction and track damage. Using the vehicle–track coupled dynamics in derailment analysis can overcome the bias of the classic theoretical methods, which use single vehicle or track system.

1.4 Research Methodology of Vehicle–Track Coupled Dynamics

Vehicle–track coupled dynamics is a highly focused technical discipline for engineering applications. It is an interdisciplinary field involving many research areas such as mechanical engineering, civil engineering, vibration mechanics, numerical analysis methods, and computer simulation technologies. To study such a complicated issue, it is generally necessary from theoretical models, numerical simulations, and field tests. The research methods should incorporate mathematical models and related experiments. The theoretical analysis should be regarded as the principal part of the research. Validations of theoretical models and simulation systems can be achieved via essential field tests. In this sense, it is also possible to reduce many expensive railway field tests, since many problems can be investigated by using validated mathematical models. However, it has to be pointed out that, for practical engineering applications, theoretical analysis results must ultimately be validated using field tests.

Due to the complexity of the wheel–rail system, the analysis of vehicle–track coupled dynamics is far beyond the scope of theoretical analysis and must be solved numerically by using computers. For large and complex systems, numerical simulations have great advantages and are widely used in modern engineering. First, numerical simulations provide detailed numerical solutions of the complex problems with less investment. Compared with the limited experimental data from field tests, numerical simulations can effectively reduce the reliance on costly experiments. For the study of vehicle–track coupled dynamics, the significance is considerable because real-vehicle tests on railway lines are usually extremely expensive and also affect normal operation of the railway. In the event of any serious accident such as an overturn or derailment during the tests, the economic loss is even greater. In contrast, it is almost always feasible to investigate various extreme conditions such as exceeding the speed limit and/or the axle load, or running over severely damaged track without any risk by utilizing numerical simulation tools. Second, the system parameters or sensitivity analysis can be carried out via numerical simulations within a short time, which enables optimal parameters of new rail transport systems to be found. Therefore, once the simulation system is tested and verified, many intermediate experiments could be largely reduced or even completely replaced by simulations. This saves considerable expense and shortens the engineering design process.

There are three essential points to realize numerical simulations of vehicle–track coupled dynamics. The first is to establish a reasonable mathematical model to describe the physical essence of the vehicle–track coupled system. The second is to choose an efficient numerical simulation algorithm that is suitable for the nonlinear solution of this complicated large-scale dynamic system. The third is to correctly determine the model parameters of the vehicle–track system.

Mathematical models are the foundation of numerical simulations. To be able to handle the complicated factors in the large-scale vehicle–track coupled system, the general influences of these factors first need to be defined. Second, the modeling method of each component in the system needs to be analyzed and then the corresponding modeling principle should be proposed via analysis and comparison. Third, based on this principle, the vertical, lateral and longitudinal interactive vehicle–track coupled model can be established. The model includes differential equations of vehicle motions and track structure vibrations, dynamic wheel–rail coupled relationships, etc. Finally, various disturbances of the wheel–rail system need to be modeled correspondingly in order to provide the excitation inputs to the vehicle–track coupled model.

Stability and accuracy are the most important requirements for all numerical simulation algorithms. The mathematical model of vehicle–track coupled dynamics can eventually be expressed as second-order differential equation sets with quite high degrees of freedom, e.g., hundreds or even thousands. Furthermore, the frequency of the wheel–rail contact vibration is very high (some components have frequencies higher than 500 Hz). Consequently, only a very small calculation step size can be adopted in the numerical simulations. Therefore, the numerical calculation speed has become a key issue of concern in the simulations. Among the existing numerical integration methods, Newmark-β method, Wilson-θ method, and Runge–Kutta method are the most commonly used ones. However, these methods often require a large amount of computation time in the simulations of large-scale engineering dynamics problems. Especially in the early studies conducted by the author (in the early 1990s), the conflict between required computing speed and available computing capacity was very prominent. Therefore, the development of a fast and practical numerical integration method, at that time, was the priority for the implementation of vehicle–track coupled dynamics simulations on ordinary microcomputers. Fortunately, a new fast explicit numerical integration method and a new prediction–correction integration method were constructed by the author [18]. The two methods have obvious advantages in numerical solutions for large-scale dynamic problems. As they do not need to solve large-scale algebraic equation sets at each time step, they are expected to be able to successfully solve the issues mentioned above.

Correct selection of model parameters plays a key role in ensuring the accuracy of numerical simulation results. For vehicle–track coupled systems, it is not very easy to determine or identify all physical parameters accurately due to the complexity of the system, especially for the track structure. This is a common problem for many engineering calculations and analyses. However, it is not always necessary to obtain completely detailed parameters for modeling. The more important thing is to specify the key parameters that characterize the system behaviors. For the vehicle system, many detailed and accurate methods for determination of vehicle parameters are widely adopted. For instance, the dimensions, mass, and inertias of the vehicle components, as well as the stiffness and damping parameters of the suspension systems can be determined or calculated using design drawings or technical documents or by means of relevant laboratory bench tests, etc. For the track system, the situation is much more complicated. However, after years of simulations and experiments, large amounts of relevant data have been collected and the systemic parameter identification methods have been gradually developed. First of all, the physical parameters and profiles of the rail can be determined for specific railway lines. Second, sleeper parameters can also be accurately determined via design standards. Third, the dynamic parameters of rail pads (stiffness and damping) can be obtained from product documents or be identified from loading tests in a laboratory. Fourth, for ballastless track which is widely used in high-speed railways, the structural parameters and physical parameters of track slab, CA mortar, and other components can be determined in more straightforward ways as they are clearly specified in high-speed railway standards. In addition, the parameters of ballasted tracks, such as ballast thickness and ballast density, can also be measured accurately or determined from design specifications. The difficult task is the identification of the stiffness and damping parameters of the ballast and subgrade. The classic axle-dropping test technique [19] and the continuous measurement techniques for track stiffness developed in recent years (especially, the track elasticity test vehicles) [20–23] have provided effective approaches to measure the overall stiffness (and even damping) of the track. It is feasible to identify accurate stiffness parameters of ballast and subgrade from the overall track stiffness, even though this work is not easy. The author believes that an effective indirect method to determine ballast and subgrade stiffness is to measure the elastic modulus of ballast and subgrade (both are easy to measure) and then calculate their stiffness parameters inversely according to the dimensions of the supporting body. This method will be introduced later in this book.

Admittedly, any simulation analysis must be based on certain experimental results. Simulation results should be validated by the corresponding tests. Focusing on practical applications of railway engineering, the simulation results of vehicle–track coupled dynamics must be verified by railway field tests. In fact, it is possible to simulate many typical large-scale wheel–rail dynamics tests and compare the simulation results with field test results. In contrast, by systemically organizing typical dynamics tests, such as vehicles passing over rail joints or negotiating curved tracks, the displacements and accelerations of key components of the wheel–rail system, dynamic wheel–rail contact forces, and other major indexes can be measured and compared with the calculation results so as to validate the vehicle–track coupled dynamics model and improve the simulation software. In addition, based on a series of full-scale field tests including the Chinese speedup tests on existing railway lines, high-speed train running tests on newly constructed high-speed railways and several derailment tests organized by the Chinese railway during last decades, a wide range of test results under various operating conditions could be utilized to validate the simulation models. These validations also enable more functions to be incorporated into the simulation system. Having gone through these systematic and extensive validation processes, the vehicle–track coupled dynamics simulation system is expected to demonstrate significant value in more extensive engineering applications.

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Chapter 2
Vehicle–Track Coupled Dynamics Models

Abstract Theoretical model is the base for the study of vehicle–track coupled dynamics problems. In this chapter, the principle and methodology for modeling of vehicle–track coupled systems are discussed at first. And then, three types of theoretical models are established: the vehicle–track vertically coupled dynamics model, the vehicle–track spatially coupled dynamics model, and the train–track spatially coupled dynamics model, in which typical passenger coaches, freight wagons, and locomotives as well as typical ballasted and ballastless tracks are included. A new dynamic wheel–rail coupling model is also established to connect the vehicle subsystem and track subsystem. Equations of motion of the vehicle and track subsystems are deduced and given in detail.

2.1 On Modeling of Vehicle–Track Coupled System

2.1.1 Evolution of Wheel–Rail Dynamics Analysis Model

The earliest involvement of wheel–rail dynamic analysis dates back to 1867, when Winkler proposed the theory of elastic foundation beam, which was quickly used for track modeling and the deformation analysis of track under static load. In 1926, Timoshenko applied the elastic foundation beam model to first study the dynamic stress of the rail under vehicle loading, which is a classical method still widely used today. In 1943, Dörr proposed that better track models should be developed to accommodate the growth speed of the train. However, few models have been developed to solve practical problems of wheel–rail contact. In the meantime, the railway researchers are more concerned about the dynamic stability of moving loads (due to rolling stock) on the beam (i.e., rail). An important reason is that in 1954, the French National Railways (SNCF) experienced severe track sinusoidal alignment irregularities in the high-speed train test with a maximum speed of 330 km/h, resulting in lateral damage to the track structure. This experience shifted the research focus in the late 50s and early 60s to the lateral running stability of rolling

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