高铁技术系列丛书

Advance in High-Speed Rail Technology

Dynamic Interaction of Train-Bridge Systems in High-Speed Railway

Theory and Applications

高速铁路车桥耦合动力学理论与应用

He Xia
Nan Zhang
Weiwei Guo

夏禾 张楠 郭薇薇 著

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内 容 简 介

本书较全面地介绍我国高速铁路的发展概况，高速铁路桥梁的特点和关键技术，车桥耦合动力学的研究历史和现状，简支梁的共振、抑振与消振机理，车桥耦合系统的自激激励，高速铁路列车-桥梁振动性能评判标准，车桥耦合振动模型的建立和求解方法，风-车-桥系统耦合振动，地震作用下的车桥耦合振动，撞击荷载作用下的车桥耦合振动，桥梁基础不均匀沉降和冲刷效应下的车桥耦合振动，桥梁徐变上拱和温度变形作用下的车桥耦合振动，以及这些研究成果在我国高速铁路桥梁设计中的应用。书中重点介绍车桥耦合振动的分析理论、研究方法及其工程应用。

本书可供铁路、城市轨道交通相关领域的科研人员和工程技术人员参考，并可作为高等学校研究生教材和本科学生的教学参考用书。

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Preface

In recent years, the high-speed railway (HSR) has got remarkable development in China. By the end of 2016, the total length of HSR lines had been 22,000 km. In addition, there are more than tens of HSR lines being constructed. According to the "Thirteenth Five-year Plan" of China, the total length of HSR lines will reach 30,000 km by 2020, and it will be further extended to 38,000 km by 2025.

The high-speed railway has the characteristics of high speed and high traffic density of trains; thus, the problem of train-bridge coupling vibrations is very prominent. On the one hand, the high-speed train will produce a dynamic impact on the bridge structure, causing it to vibrate, which directly affects the working status and the service life of the bridge. On the other hand, the vibration of the bridge will in turn affect the running safety and stability of the on-bridge train. This makes the vibration behaviors of train-bridge system become one of the fundamental problems that need to be solved in the bridge design. It is an actual requirement for engineers to carry out comprehensive studies on the dynamic interaction of the coupled train-bridge system. This includes the dynamic analysis and assessment on the dynamic properties of the bridge structure, as well as the running safety and stability of the high-speed train. Therefore, great efforts have been continuously made to study the dynamic interaction between high-speed train and bridge. After years of development, the coupling vibration of train-bridge system has become a specialized research field.

In China, researchers have established a number of analysis models, performed systematic study on the dynamic responses of train-bridge interaction system, and achieved remarkable results for the actual engineering projects, making important contribution to the dynamic design of HSR bridges.

This book is the fruitful result of the research projects sponsored by the National Key Basic Research Program ("973" Program, 2013CB036203), the National High-technology Research and Development Program (863 Program, 2011AA11A103-3-2-1), the Natural National Science Foundations (Grant No. 51078029, 511780255, 51208027, 51208028, 51308034, 51308035, U1434205, U1434210, and 51678032), the Research Fund for Doctoral Program of Higher Education (20130009110036), and the Supporting Program for New-century Excellent Talents in Universities (NCET-10-0219) of China, the Science and Technology Research Plans of China Railway Corporation (2013G001-A-1, 2013G001-B, 2013G004-C, 2015G002-A and 2015G006-M), and the Flanders (Belgium)-China Bilateral Project (Grant No. BIL 07/07).

In Chap. 1, starting with a general overview of HSR developments in China and abroad, the key technologies of HSR bridge construction in China are introduced, the research history and status quo of train-bridge coupling vibration are reviewed, the dynamics problems of HSR bridges are summarized, and the research contents and analysis methods for coupling vibrations of train-bridge system in HSR are expounded.

In Chap. 2, some fundamental theories and methods for vibration analysis of simply-supported beams under moving loads are presented. The analytical solutions of beam vibrations induced by a moving concentrated load, a moving harmonic load, and a moving wheel-spring-mass load with varying speed are deduced, and the vibration characteristics of them are investigated in several case studies. As one of the important phenomena related to the train-bridge coupling vibration, the mechanisms of vibration resonance, suppression, and cancellation happened in the moving-load and beam system are analyzed.

In Chap. 3, the self-excitations of train-bridge coupling vibration system are introduced. The characteristics and control standards of track irregularities, and the mechanism and description of vehicle hunting movement are summarized. The AR (auto-regressive) model simulation method of random excitations on the train-bridge system is studied.

In Chap. 4, the vibration criteria for HSR bridges and train vehicles in China are summarized, including a series of codes, standards and specifications related to the dynamic coupling analysis and test of train-bridge system, the control criteria for running safety of high-speed train due to bridge and train vibrations, the riding comfort of passengers on running train vehicles, and the structural safety serviceability of bridge due to vibrations. The conditions unnecessary to conduct coupling dynamic analysis of train-bridge system are also introduced.

Chapter 5 recapitulates the dynamic analysis models for train-bridge coupling system and the solution methods. The motion equations for the train-bridge coupling vibration system are derived. The solution methods for motion equations of train-bridge system, such as the direct coupling method, the in-time-step iteration method, and the intersystem iteration method, are studied. By taking a Pioneer EMU running through a multi-span simply-supported PC box-beam bridge on the Qinhuangdao-Shenyang HSR line as an illustrating example, the dynamic responses of train-bridge system are analyzed and the convergence in equation solution procedure is investigated.

Chapter 6 studies the vibration of coupled train-bridge system subjected to crosswinds. The influences of wind barriers on the wind velocity field around bridge structure and the aerodynamic behaviors of train vehicles are investigated. A spatial dynamic analysis model of train-bridge system subjected to crosswinds is established. The dynamic responses of the Tsing Ma Suspension Bridge in Hong

Kong are calculated, and some results are compared with the measured data, from which the threshold curve of train speed and wind velocity for ensuring the running safety of the train on the bridge is proposed. Considering the aerodynamic effect of wind barriers on a simply-supported PC girder bridge, the dynamic responses of the wind-train-bridge system are calculated, and the windbreak effect of different wind barriers is evaluated.

Chapter 7 deals with the vibration of train-bridge system subjected to earthquake action. The spectral theory-based simulation method for seismic ground motion considering spatial variation and the method for obtaining consistent earthquake record are summarized. The dynamic analysis models of a single wheel-spring-mass unit (series) passing through a simply-supported beam as well as the train-bridge system subjected to earthquakes are established. The dynamic responses of an ICE3 train passing through a steel trussed-arch bridge subjected to earthquakes are calculated, and the influences of the seismic characteristics and the input manners on the dynamic responses of train-bridge system are investigated. The running safety criteria and evaluation process of train vehicles on bridge subjected to earthquakes are proposed.

Chapter 8 is devoted to the vibration of train-bridge system subjected to collision loads. The characteristics of various collision loads on bridge are summarized. A dynamic analysis model is established for a coupled high-speed train and bridge system subjected to collision loads. An HSR double-track continuous bridge with (32+48+32) m PC box-girders is considered as an illustrative case study. The dynamic responses of the bridge and the running safety indices of the train on the bridge under three types of collision loads are analyzed. The results show that the large responses of the bridge induced by collision may strongly threaten the running safety of the train. An assessment procedure is proposed for the running safety of high-speed trains on bridges subjected to collision loads, and related threshold curves for train speed versus collision intensity are proposed.

Chapter 9 deals with the vibration of train-bridge system under differential settlement and scouring effect of foundations. The influence factors of differential settlement and the mechanism of scouring effect of pier foundations are summarized. A prediction method for cumulative settlement of bridge foundations caused by cyclic train loading is proposed, and the settlement of existing bridge foundations induced by the nearby bridge construction is calculated. The influence of differential settlement of bridge foundations on dynamic responses of train-bridge system is studied, and the train speed-settlement threshold curves for running safety and riding comfort of train are proposed. The stiffness of a single pile and the equivalent stiffness of group piles are studied, and the scouring effect on the stiffness of bridge foundations and the dynamic responses of the train-bridge system is investigated.

Chapter 10 deals with the vibration of train-bridge system under beam deformation induced by concrete creep and temperature effect. The numerical simulation method for PC beam creep camber is introduced. The vibration responses of train-bridge system excited by creep camber deformation are analyzed, and the safety threshold curves of creep camber under different train speeds are proposed, to ensure the running safety and stability of train vehicles. By numerical simulation and field measurement, the characteristics of bridge sidewise-bending and track slab-warping deformation under non-uniform temperature field are studied, and their influences on the dynamic response and running safety of the train-bridge system are investigated.

This book will not only provide theoretical formulations and various solutions for coupling vibrations of train-bridge system, but also describe the ways to extend the life of existing bridge structures and present a guide to the rational design of new bridges. It can also be referenced for solving vehicle–structure dynamic interaction problems in the design and the research of various types of highways, railways, and other transport structures.

This book is chiefly authored by H. Xia, N. Zhang, and W.W. Guo, with Chapter 1 written by H. Xia, N. Zhang, W.W. Guo, and Y.M. Cao; Chapter 2 by H. Xia, H.L. Li, K.P. Wang, and S.Q. Wang; Chapter 3 by W.W. Guo; Chapter 4 by N. Zhang; Chapter 5 by N. Zhang and X. Wu; Chapter 6 by W.W. Guo and T. Zhang; Chapter 7 by X.T. Du; Chapter 8 by C.Y. Xia; Chapter 9 by Y.M. Cao and K.P. Wang; and Chapter 10 by J.W. Zhan and K.P. Wang. In addition, the work by Y. Tian, K.B. Li, J.J. Yang, H. Qiao, M. Xu, S. Zhou, Y.J. Wang, Q. Sun, G.H. Ge, G.L. Xiao, and other graduate students also contributed to the related chapters.

In writing this book, we drew much on the knowledge and experience acquired from collaboration with many colleagues in China and abroad. We wish to express our deep appreciation to them. We also acknowledge the information and inspiration derived from the references listed at the end of the chapters.

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Chapter 1
Introduction

Since its occurrence, railway has been the focus of the world transportation. Entering the twenty-first century, railway construction has been speeded up in China to improve the passenger and freight transports. Especially, the development of high-speed railway has made remarkable achievements. As an infrastructure, bridges play a very important role in high-speed railway. With continuous raise of train speed, the bridge vibrations and their influences on running safety and stability of trains have drawn more attention. This chapter summarizes the key dynamics problems of high-speed railway bridges, reviews the research background and current status of train-bridge coupling vibration, and expounds the corresponding research contents and analysis method for coupling vibrations of train-bridge system in high-speed railway.

1.1 High-Speed Railways in China

1.1.1 Development of High-Speed Railways

The railway traffic has got great development with its safety, punctuality, and high efficiency since it appeared in England in 1825. With the progress of society and the development of science and technology, the demand for railway transport capacity is increasing, as well as for the train speed. According to UIC (Union Internationale des Chemins de Fer) in 1996, "new tracks specially constructed for high speeds, allowing a maximum running speed of at least 250 km/h, or existing tracks specially upgraded for high speeds, allowing a maximum running speed of at least 200 km/h" are defined as high-speed railway (HSR).

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