AN INTEGRATED COUPLING ELEMENT FOR VEHICLE-RAIL-BRIDGE INTERACTION SYSTEM WITH A NON-UNIFORM CONTINUOUS BRIDGE**

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ABSTRACT An integrated coupling element considering wheel-rail interface for analyzing the dynamic responses of vehicle-rail-bridge interaction system with a non-uniform continuous bridge is presented. The governing equations of the interaction system are established first, and the solution procedure and assembly method of the coupling element are demonstrated. Finally, the accuracy, efficiency and function of the integrated coupling element are tested using two numerical examples. The influences of different combinations of rail and bridge element length in the coupling element on the solution are investigated, and the effects of different rail irregularities on the dynamic responses are discussed.

KEY WORDS vehicle-rail-bridge dynamic interaction, integrated coupling element, non-uniform continuous beam, wheel-rail contact, rail irregularity

I. INTRODUCTION

High-speed railway transportation provides a viable alternative to both aviation and highway transportation; however, it continues to suffer new technical problems. Recently, the dynamic behaviors of bridges on high-speed railways have received increased attention, and many influential studies have been published over the past two decades[1–3]. In general, two types of methods, i.e., analytical and numerical methods, have been used in these investigations. Analytical methods are simple and clear, but not suitable for analyzing the complex dynamic behaviors of railway bridges[2]. However, the finite element method (FEM) has been widely used in this field as a powerful numerical means by many researchers[4–7]. Based on FEM and structural dynamics, various coupling elements have been proposed. Yang and Yau[4] first presented a vehicle-bridge element to model the vehicle-bridge dynamic interaction. Thereafter, Yang et al.[5] and Wu et al.[6] improved the vehicle-bridge element by considering the pitching effect of the vehicle. Ju and Lin[7] considered vehicle braking and acceleration in their analysis of a vehicle-bridge interaction system. In these studies, the vehicle-bridge element did not take into account the effects of rail structures, which were mainly applicable to the vehicle-bridge coupling system.

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However, maintenance workers of French and German railways have reported destabilization of the ballast on small and medium span bridges on high-speed railway lines\cite{8}. This phenomenon could result in serious consequences, such as the possibility of derailment and increased maintenance costs. This means that rail structure cannot be ignored in the dynamic analysis of interaction system. Accordingly, Cheng et al.\cite{10} developed a bridge-track-vehicle coupling element to examine the interactions of the train, the rail and the bridge. In order to provide an effective and convenient way to analyze train-track dynamics, Koh et al.\cite{11} presented a new approach called the moving element method, which allowed the use of different element sizes for improving model efficiency. Based on the stationary value of the total potential energy of the coupling dynamic system, Lou\cite{12} presented a vehicle-track-bridge interaction element considering the pitch effect of the vehicle to analyze the vehicle-track-bridge dynamic interaction, in which the vehicle was modelled as a two-axle mass-spring-damper system with 4 degrees of freedom (DOFs).

Considering the rail structure, Lou et al.\cite{13,14} utilized the finite element method to analyze the vehicle-track-bridge interaction by modelling the vehicle as a mass-spring-damper system with 10 DOFs. Lou et al.\cite{15} also developed a special rail-bridge coupling element to improve the computational efficiency, in which the length of the uniform bridge element was longer than that of the rail element. In the two methods, the rail and the bridge were modelled as an elastic Bernoulli-Euler upper beam and a simply supported Bernoulli-Euler lower beam, respectively, while the elasticity and damping properties of the ballast were represented by continuous springs and dampers, respectively. It is true the aforementioned analytic models can be used in vehicle-track-bridge systems, they simplify the interaction between the wheel and the rail. Since the wheelsets are assumed to always maintain contact with the rail, these approaches cannot simulate the jump of wheels or derailment.

As transient jump of wheel can occur, the wheel-rail contact should be simulated more precisely. Contact models using linear or nonlinear Hertz springs have been widely used to examine the interaction between the wheel and the rail, with many notable achievements reported in the past decade or so\cite{16-20}. Cheng et al.\cite{20} investigated the onset and effects of separation between a moving vehicle and the bridge. Using a linear Hertz spring to model the wheel-rail contact, Bowe and Mullarkey\cite{21} and Zhang et al.\cite{22} analyzed the dynamic responses of the train-bridge interaction. Besides, adopting the same contact model, Liu et al.\cite{23} studied the separation between a vehicle and the bridge, and by considering random and abrupt irregularity on the bridge, the transient jump of wheel was also discussed. It is worthwhile to point out that these analytic models are almost all oriented toward structures with girders of uniform cross-section and depth.

Although the non-uniform geometric properties of bridges make the vehicle-rail-bridge system complicated, it has still received considerable attention from researchers owing to the demands of practical engineering. Leung\cite{24} presented a new method to form the element matrices for non-uniform frames based on the Galerkin method. Zheng et al.\cite{25} analyzed the vibration of a multi-span non-uniform beam under moving loads using the modified beam vibration functions. Using both the modal analysis method and the direct integration method, Dugush and Eisenberger\cite{26} investigated the dynamic behavior of multi-span non-uniform beams travelled over by a moving load. Furthermore, by modelling the structure as Bernoulli-Euler beam elements, Martínez-Castro et al.\cite{27} presented a semi-analytic solution for the moving load problem, which is of great importance to the analysis of multi-span non-uniform beams subjected to moving forces, such as high-speed trains. Based on practical engineering applications for high-speed railway bridges, a comprehensive model of the vehicle-rail-bridge interaction system should address not only the vibration of the vehicle, the rail and the bridge, but also the wheel-rail contact and the rail-bridge connection. Unfortunately, few of the research objectives were addressed in existing studies (at most 1 or 2 of them) to merit mention. Thus, in order to meet the requirements of complex railway bridges, it is necessary to develop a powerful integrated coupling element for the vehicle-rail-bridge interaction.

In this paper, an integrated coupling element for analyzing the dynamic responses of a multi-span non-uniform continuous bridge travelled over by high-speed trains is presented. In this vehicle-rail-bridge interaction model, the vehicle is modelled as a mass-spring-damper system with 10 DOFs, with the rail bed represented by continuous springs and dampers. Wheel-rail contact interaction is simulated by a series of linear Hertz springs\cite{21-23}, while the rail and the bridge are modelled as an elastic Bernoulli-Euler upper beam with finite length and a multi-span non-uniform Bernoulli-Euler