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A nonlinear multi-spring tire model for dynamic analysis of vehicle-bridge interaction system considering separation and road roughness

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ABSTRACT

This paper proposes a nonlinear multi-spring tire (NMST) model for dynamic analysis of vehicle-bridge interaction (VBI) system considering separation and surface roughness. First, a nonlinear single-spring tire (NSST) model is developed, which can only provide compression force rather than extension force. By introducing it into VBI system, the dynamic interaction problem considering separation and road roughness becomes a typical dynamic problem with material nonlinearity which can be easily solved by the combination of Newmark method and Newton method: the coupled governing equations never change whatever the tire separates from the bridge or not. It is more convenient because iterative process is required in conventional method to check the separation status and once separation occurs, the coupled governing equations have to change and decouple into independent equations corresponding to vehicle and bridge, respectively. It is then extended to NMST model which is more realistic because the contact surface of tire and road are of finite size instead of a point and the tire usually cannot touch the bottom of valleys in the road profile. In the numerical examples, it can be found that the dynamic responses of both bridge and vehicle obtained by NMST model are better than those obtained by NSST model because they have lower high frequency components, which is closer to the observation in the field testing. The proposed NMST model can be easily incorporated into various VBI models, which benefits for numerical study of dynamic responses of both vehicle and bridge and indirect methods to identify modal properties and local damage of bridge structures.

1. Introduction

The vehicle bridge interaction (VBI) problems have been extensively investigated for many years [1,2], including numerical simulations and field testing. The numerical models are frequently used because they are more convenient and cheaper. One of the most important application in engineering is to investigate the dynamic responses of the bridge induced by passing vehicles. Another important application is to study indirect method [3,4] to identify modal properties and damage of bridges in which the vehicle performs as both “exciter” and “massage carrier”. Recently, it becomes increasingly popular because it is convenient, and it is “a step toward mobile infrastructure informatics in a large urban setting [5]”. The dynamic responses of

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the VBI system, especially for the accelerations, are usually used in these methods [6–9] and the accuracy is highly dependent on the adopted model; therefore, it is quite important to generate a suitable finite element (FE) model to make the numerical simulation results more meaningful. The independent bridge and vehicle can be modelled quite well; the most difficult part is the interaction between the vehicle and the bridge. Attention should be paid on two issues to make the FE model more accurate.

The first issue is the contact condition between the vehicle tire and the bridge surface. The majority of frequently used FE models assume that the tire and the bridge surface are in permanent contact. Usually there are two approaches to simulate the permanent contact between the bridge and vehicle: one is to consider the vehicle and bridge separately [10–12] and an iterative process in each time step is required to achieve equilibrium between bridge and vehicle; the other is to couple the VBI system in which the vehicle is in sliding contact with the bridge and the dynamic responses can be obtained by numerical integration in time domain [13–19]. Although separation between the tire and bridge surface is not frequently observed, it should be carefully considered in FE models when the road surface roughness is included. Lee [20] studied the separation between the moving mass and the supporting structure for the first time and indicated that “the separation of the mass from the beam may occur at relatively slow speed and small mass”. Lee [21] conducted the dynamic analysis of a mass passing through a beam in which the contact force was set to zero once the separation occurred and then the coupled equations were decoupled into two independent equations during the separation. Cheng et al. [22] investigated the separation between moving vehicle and bridge and proposed an algorithm to calculate the dynamic responses at the moment of reattachment. Stancioiu et al. [23] and Baeza and Ouyang [24] also studied the effect of separation and further simplified the calculation of dynamic responses after the impact. Then research [25–27] has been conducted to investigate the effect of road roughness and the separation and reattachment on the safety and serviceability of structures. Usually, one motion equation is required for the vehicle when the separation occurs because the vehicle is simplified as a single oscillator which has only one tire modelled as either a point mass or a massless point. Stancioiu et al. [28] investigated a two-wheel vehicle passing through a bridge and they found that three equations of motion were required because there are three different scenarios of separation. Therefore, when a vehicle model containing multiple tires is used, it becomes quite complicated for conventional method due to different separation scenarios. To overcome this difficulty, Zhu et al. [29] recently considered the VBI interaction problem as a standard linear complementarity problem and a vehicle model with three bodies and four wheels were investigated.

The other issue is that the contact area between the vehicle tire and the bridge surface, which is usually modelled as a point [30–32]. The single point model performs well when the road surface is smooth; however, some researchers [33–36] found that the numerical model of VBI in which the contact area treated as a point is not accurate if the road roughness is considered. Chang et al. [33] observed that the point model accompanied with the road profile generated by power spectrum density (PSD) approach would induce high frequency vibrations; therefore, they developed a rigid disk model to simulate the tire passing through rough surface. Yin et al. [34] also developed a disk model for tires which considered the tire deformation. Deng et al. [35] recently proposed a multi-point tire model and they used a series of linear springs instead of a single spring point model. They concluded that the multi-point tire model could predict more accurate bridge responses than the conventionally used single-point model and it can save additional computational resource. Ding et al. [36] also used similar model to investigate the effect of the dynamic impact at modular bridge expansion joints. However, in their model the vehicle should be in permanent contact with the bridge.

Therefore, considering these two issues, it is easy and reasonable to conclude that the combination of Zhu's model [29] and Deng's model [35] is ideal for dynamic analysis of VBI systems considering both separation and road surface roughness. However, it is not easy to combine these two models directly because the linear complementarity problem in Zhu's model [29] becomes quite complicated if multiple springs are used for one tire. On the other hand, both the two models are not suitable for VBI system containing material nonlinearity. In this paper, a nonlinear single-spring tire (NSST) model which performs as well as Zhu's model [29] is proposed first so that the coupled equations of motion never change whatever the vehicle separates from the bridge or not; and then it is extended to a nonlinear multi-spring tire (NMST) model. By introducing it into the VBI system, this problem becomes a typical dynamic problem with material nonlinearity which can be easily solved by the combination of Newmark method and Newton method. It should be acknowledged that 3-D vehicle model is preferred in investigating the dynamic responses of VBI system, while it can be improved by using the proposed NMST model to replace the conventionally used point model of tire. Numerical examples have been conducted to verify the equivalence of the proposed NSST model and Zhu's model [29]. The comparison of NSST and NMST models show that the latter can predict more realistic dynamic responses than the former because amplitudes of high frequency components in dynamic responses can be effectively reduced. Moreover, a numerical example of VBI system with nonlinear suspension system and nonlinear stiffness and damping coefficients under compression is also presented.

2. Finite element model

2.1. Nonlinear tire model

NSST and NMST models are proposed in this study, which can be seen in Fig. 1. For NSST model, besides the mass of tire and bogie assemblies, m_t, there is only one single spring providing compression force instead of tension force; therefore, the stiffness and damping coefficient can be expressed as: