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Fully coupled driving safety analysis of moving traffic on long-span bridges subjected to crosswind

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ABSTRACT

High-sided vehicles often experience considerable single-vehicle accident risks under crosswinds. Long-span cable-supported bridges are usually flexible, wind-sensitive and support considerable amount of vehicles on a daily basis. When vehicles are driven through a long-span bridge, the complex dynamic interactions among wind, vehicles and the bridge significantly affect not only the safety of the bridge members, but also passing vehicles. Therefore, realistic modeling of the bridge–traffic system by characterizing these critical coupling effects becomes essential for rationally assessing traffic safety of passing traffic through a long-span bridge. In most existing studies about traffic safety study on bridges, vehicle safety was assessed for only one single vehicle or uniformly distributed vehicles at a constant driving speed. It is known that the traffic flow on a long-span bridge is typically stochastic and vehicle speeds vary following some traffic rules. Based on the stochastic traffic flow simulation, two new analytical frameworks, one using mode superposition and the other using the finite element (FE) formulation, were proposed recently for the bridge–stochastic traffic system. By considering the full-coupling effects among all the vehicles of the traffic flow, bridge and wind, the dynamic response of each individual vehicle of the stochastic traffic can be accurately obtained for the first time. Built based on the recent advances made by the authors, an integrated dynamic interaction and safety assessment model of the fully-coupled bridge–traffic system is further developed without considering vehicle aerodynamic interference and shielding effects. Traffic safety of vehicles in the stochastic traffic through the prototype long-span cable-stayed bridge is investigated as a demonstration.

1. Introduction

Highway vehicles may experience single-vehicle accidents under hazardous driving environments, such as strong crosswind, slippery road surface with rain, snow or ice, etc. (USDOT, 2005). For traffic through flexible transportation infrastructures, such as bridges, single-vehicle accident risks were found to increase due to the dynamic coupling effects between the vehicle and the supporting structure (Baker, 1991; Guo and Xu, 2006). Long-span bridges are usually built across straits or major rivers, and therefore they are more open than most roads with less blocking effects from surrounding environment, exposing vehicles to stronger crosswind. Long-span cable-supported bridges are flexible, susceptible to wind excitations and support considerable amount of vehicles on a daily basis. In addition, vehicles driven on long-span cable-supported bridges may also be temporarily shielded from the crosswind by the bridge tower or other nearby high-sided vehicles, experiencing sharp crosswind gust as well as higher accident risks. When vehicles are driven through a long-span bridge, the complex dynamic interactions among the wind, vehicles and bridge significantly affect not only the performance of the bridge, but also the safety of passing vehicles (Chen and Wu, 2010; Chen and Cai, 2004; Guo and Xu, 2006). Therefore, a rational traffic safety assessment of passing traffic through a long-span bridge requires appropriate modeling of the critical coupling effects within the bridge–traffic–wind system.

Baker (1986, 1987, 1991, 1994) started series of studies on the safety of road vehicles under sharp crosswind gusts primarily on roadways. Guo and Xu (2006) conducted vehicle safety analysis of one single vehicle by considering the bridge–vehicle interaction effects subjected to high wind. In the studies by Chen and Cai (2004) and Chen et al. (2009), the authors developed a local vehicle accident assessment model and combined it with the global bridge–vehicle interaction model to consider the vibrating effects from the bridge structure in the windy environment. Chen and Chen (2010) further developed a general local single-vehicle accident model with new transient dynamic equations and accident criteria to

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consider more realistic weather environment and topographical conditions, which can also be used on bridges with some approximations. In all these existing studies about traffic safety on bridges, vehicle safety was assessed with only one single vehicle at a constant driving speed.

In reality, it is known that the traffic flow on a long-span bridge is typically stochastic and vehicle speeds may vary following some realistic traffic rules (Chen and Wu, 2011). This is especially true when the bridge span is long and the total number of vehicles on the bridge at a time is not small. Apparently, to assume only one vehicle on the bridge with constant speed cannot reflect the realistic situations on most long-span bridges. Among all the technical hurdles preventing researchers from carrying out more realistic traffic safety assessment, the primary one is the difficulty on reasonably modeling the full dynamic interaction effects of the bridge–traffic system subjected to wind. Chen and Wu (2011, 2010) incorporated the stochastic traffic flow simulation into the bridge–traffic interaction analysis, offering a venue to more realistically simulate the dynamic interactions of multiple-vehicle scenarios from stochastic moving traffic on a long-span bridge. However, the approach was based on the equivalent-dynamic-wheel-loading (EDWL) concept (Chen and Wu, 2010), which focused on the bridge response without being able to provide accurate estimation of the dynamic response of individual vehicles of the simulated stochastic traffic (Zhou and Chen, 2014a). As a result, hurdles still remained on assessing vehicles safety on long-span bridges when stochastic traffic is simulated until recently when some advances on modeling techniques were made.

Recently, Zhou and Chen (2014a, in preparation) proposed new mode-based and FE-based dynamic analysis frameworks of the bridge–traffic system by considering the full-coupling effects of all the vehicles, the bridge and the wind simultaneously. The dynamic response of each individual vehicle of the stochastic traffic can be accurately obtained for the first time, which provides essential basis for the advanced traffic safety assessment of more realistic traffic flow. Built based on the recent advances by the authors (Zhou and Chen, 2014a, under review), the present study reports the efforts on developing an integrated dynamic interaction and safety assessment model of the fully coupled bridge–traffic system. Developed within the same simulation framework, the dynamic bridge–traffic interaction analysis is conducted to obtain the vehicle response considering road roughness and wind excitations, followed by vehicle safety assessment of different accident types for the stochastic traffic flow in the windy environment. A prototype long-span cable-stayed bridge and the simulated stochastic traffic are studied as a demonstration of the proposed approach. Due to the lack of the reliable experimental data, aerodynamic interference and shielding effects on the vehicles and the bridge are not considered in this study.

2. Mathematical modeling of the vehicles and the bridge

2.1. Modeling of the long-span cable-supported bridge

A long-span cable-stayed bridge is modeled in this study as a three-dimensional finite element model using two types of finite elements. The bridge girder and pylon are modeled with nonlinear spatial beam element based on Timoshenko beam theory. The axial, bending, torsional warping and shear deformation effects are considered at the same time. The stay cables are modeled with catenary cable elements. They are derived based on the exact analytical expression of differential equations for elastic catenary elements. The geometric nonlinear effect of axial forces on the bridge girder and pylons and the cable tension can be taken into account. The effects of flexibility and large deflection in the cables are also considered in establishing the equilibrium equations of the element. Rayleigh damping is assumed to model the structural damping of the bridge, in which the participating factors for the stiffness and mass matrices are obtained from two structural damping ratios associated with two specific modes.

2.2. Modeling of the road vehicles

Three types of vehicles are involved in the present study, which are high-sided heavy trucks, light trucks with medium height and light sedan cars. Each type of vehicle is modeled as several rigid bodies and wheel axles connected by series of springs, dampers and pivots. The suspension system and the elastic tires are modeled as springs in the upper and lower positions, respectively. The energy dissipation is achieved by modeling upper and lower viscous dampers for the suspension system. The masses of the suspension system and the tires are assumed to be concentrated on the mass blocks at each side of the vehicle and the masses of the springs and dampers are assumed to be zero. Each main rigid body contains four degrees of freedom, including two translational and two rotational ones. The numerical dynamic model of the heavy truck is composed of two main rigid bodies, three wheel axle sets, 24 sets of springs and dampers vertically and laterally, as shown in Fig. 1. The displacement vector d_v of the heavy truck model involves 19 independent DOFs including 8 in vertical, 8 in lateral and 3 in rotational directions, as defined in Eq. (1).

$$d_v = \{Z_{r1}\ \theta_{r1}\ \beta_{r1}\ Z_{r2}\ \beta_{r2}\ Z_{a1L}\ Z_{a1R}\ Z_{a2L}\ Z_{a2R}\ Z_{a3L}\ Z_{a3R}\ Y_{r1}\ Y_{r2}\ Y_{a1L}\ Y_{a1R}\ Y_{a2L}\ Y_{a2R}\ Y_{a3L}\ Y_{a3R}\} \tag{1}$$

where Z_{ri} represents the vertical displacement of the ith rigid body; θ_{ri} represents the pitching displacement of the ith rigid body in the x–z plane; β_{ri} represents the rotational displacement of the ith rigid body in the y–z plane; $Z_{aiL(R)}$ represents the vertical displacement of the ith wheel axle in the left (right) side; Y_{ri}

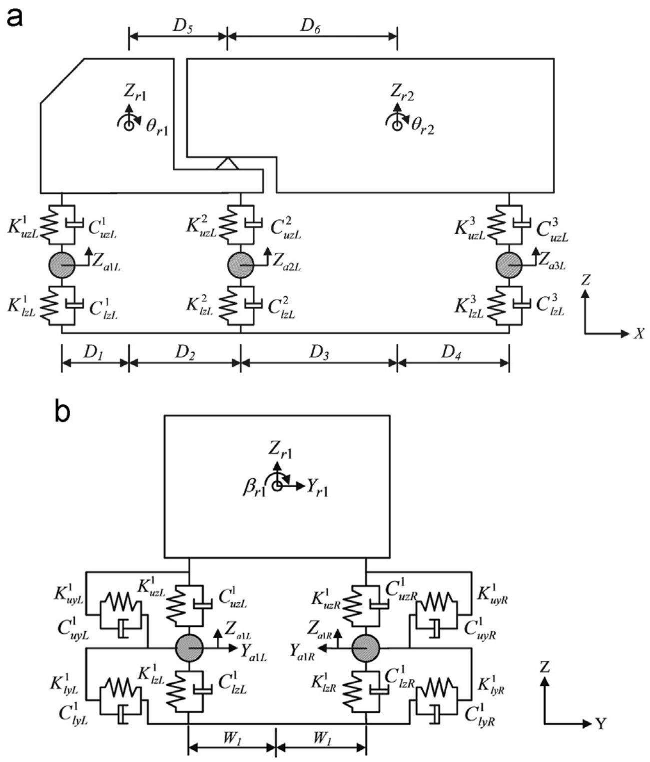

Fig. 1. The numerical dynamic model for high-sided heavy truck with one trailer. (a) Elevation view and (b) side view.