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Wind loads of moving vehicle on bridge with solid wind barrier

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ABSTRACT

A wind tunnel experimental study is conducted to study the wind loads acting on a moving vehicle model on a bridge installed with a solid wind barrier. The repeatability of the tests is verified by the cases with different wind and vehicle speeds. For comparison purposes, the difference of the results between the static and moving vehicle models are discussed. The effects of different heights of wind barriers and wind directions on the wind loads acting on the vehicles are analyzed. Finally, the wind loads acting on the vehicles are further evaluated to assess the potential impact of wind barriers on traffic safety. The results show that the relative movement between the vehicle, bridge and solid wind barriers affects the aerodynamic characteristics of the vehicle. The variation patterns of aerodynamic characteristics with different yaw angles are altered by the solid wind barriers with different heights, and there is a most unfavorable yaw angle for the protective effect of solid wind barriers in terms of side force. The wind direction has some impact on the five-component coefficients of vehicles after installing a solid wind barrier. However, the solid wind barrier has similar protective efficiency in terms of the side force acting on the vehicle under different wind directions.

1. Introduction

With the development of high-speed railways and highways, safety of vehicles under crosswinds is a serious concern attracting increasing attention. To reduce the wind loads acting on vehicles, there are typically three types of mitigation approaches [17]: shape optimization of vehicles, strong wind monitoring and warning system, and installation of wind barriers. The first type of approach is usually applied to the design of new vehicles. The second type requires the development of a complex monitoring system with high demands on prediction accuracy, long-term reliability and maintenance cost. The third type is an efficient passive approach, which can modify the local wind environment with reduced wind loads to improve the safety performance of vehicles.

The mechanism of a wind barrier can be interpreted in the way that the wind barrier practically exerts drag force on the wind field, causing a transformation of energy in the air flow, and creating a protective effect [12]. Thus, the wind speed in the wake of wind barrier can be studied to evaluate the performance of wind barriers. Kwon et al. [16] studied the effect of wind barriers on the distribution of mean wind speeds at different traffic lanes, and they provided design criteria of wind barriers. Xiang et al. [19] provided a profile of pressure coefficients above the track with three types of line structures. Su et al. [18] studied the flow distribution of full-scale wind barriers with wind tunnel tests. They discussed the effects of pore size and opening forms, and indicated that the influence of the scale effect is significant for porous wind barriers. Since the efficiency of the single point test method is low, Kozmar et al. [14] studied the mean velocity fields and vorticity fields behind wind barriers using the PIV technique. The effects of the porosity and heights of wind barriers were discussed and optimal wind barrier parameters were suggested [15]. Avila-Sanchez et al. [1] also used the PIV to measure the flow distribution on bridge decks with a solid wind barrier, as well as the mean velocity, turbulent kinetic energy, and turbulence intensities etc.

People also evaluated the performance of wind barriers by directly investigating the vehicle dynamic response. Charuvisit et al. [5] studied the vehicle dynamic response when a car passes a bridge tower in the presence of wind barriers. They found that the side acceleration and yaw angular acceleration were reduced effectively. Zhang et al. [24] used the wind-train-bridge model to study the effect of wind barriers on the dynamic response of trains, and the critical train speeds with respect to different wind velocities were proposed. Xiang et al. [19] also studied the dynamic response of trains with the coupling vibration methods, and the protective effect of wind barriers was evaluated by the Data Envelopment Analysis (DAE) method.

Coleman and Baker [8] tested the wind loads of a vehicle model behind porous wind barriers and the results indicated that the side drag and lift force coefficients of vehicles were considerably decreased because of the wind barriers. Xiang et al. [19,20] tested the aerodynamic

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characteristics of static vehicles with balance sensors. The results showed that the dependence of the drag coefficients on Reynolds number was stronger after installing the porous wind barrier, and there was a clear change for the lift-drag ratio of the train. He et al. [11] tested aerodynamic characteristics of vehicles on bridges using the pressure measurement. Avila-Sanchez et al. [2] studied the protective effect of wind barriers on embankments by the pressure measurement method. They indicated that if the windbreak was high enough, side force and rolling moment coefficients would become reversed. Guo et al. [13] also used the pressure measurement of static vehicle models to study the protective effect of wind barriers on bridges and it was found that wind barriers exhibit good performance. Charuvisit et al. [5] used a moving vehicle model test to study the protective effect of wind barriers near the bridge tower. Moving vehicle model is usually preferred to study the performance of wind barriers because static vehicle model on bridges cannot simulate the relative movement between wind barrier, vehicle and bridge deck. In addition to wind tunnel testing, computer fluid dynamic (CFD) method has also been applied to consider the relative movement between bridge deck, wind barrier and vehicle [7]. As compared to the results from the wind tunnels, the accuracy of numerical simulation with CFD still needs to be further improved.

All the existing studies as summarized above provide helpful information about the performance of wind barriers, and were primarily focused on wind fields, vehicle dynamic responses, or the aerodynamic forces on vehicles. Wind field can be related to the change of wind loads acting on vehicles to some extent. However, it cannot capture the interaction between the wind field and the vehicle [21]. Ideally, a full evaluation of the protective effect of wind barriers needs to be made based on the safety performance assessment of vehicles under crosswind [6]. Such an approach requires a complex dynamic interaction model, which can be specific to the supporting structures (e.g. bridge). Alternatively, the vehicle aerodynamic coefficient has a similar changing pattern with different wind barrier parameters [19]. Hence, aerodynamic characteristics of vehicles can also serve as a good performance indicator to evaluate the performance of wind barrier [22].

In this study, a moving vehicle model device is used to simulate the movement of vehicle on bridges with a solid wind barrier, and the wind tunnel tests are conducted to measure the wind loads of moving vehicles. Different from most existing studies focusing on static vehicle models, the present study is the first one that adopts a moving vehicle model at a pretty high speed to evaluate the performance of wind barriers. In Section 2, an overview of the moving vehicle model device, data processing and test cases is made. The effects of wind speed, vehicle movement, wind barrier height and wind direction are discussed in Section 3.

2. Wind tunnel experiments

A moving vehicle device [23] is used to obtain the aerodynamic characteristics of vehicles under crosswinds. The cross-sectional schematic view of the moving vehicle device is shown in Fig. 1, and the photos of the moving vehicle device are shown in Fig. 2. Experiments are carried out in the XNJD-3 wind tunnel of Southwest Jiaotong University, which has the peak velocity near 16.5 m/s. The turbulence intensity of the free-stream flow I_x is less than 1.5%, and the wind field has a good uniformity along the width of the wind tunnel [23]. As a return-flow type wind tunnel, the length, width and height of the test section of the wind tunnel used in this study are 36.0 m, 22.5 m and 4.5 m, respectively.

As a part of the moving vehicle device, a linear module, which consists of synchronous belt, guideway, slide table, etc., works as a guideway. The servo motor can be directly installed on the linear module with the coupling and flange, and drive the slide table from one side to the other side by the synchronous belt. The vehicle speed can be adjusted between 0.5 m/s and 10.0 m/s. The linear module has a length of 10.0 m, a width of 0.08 m and a height of 0.08 m. To avoid the interference of the linear module on the flow field of bridge decks, the linear module is housed inside the bridge model and supported by a horizontal adjustment plate, connected to the wind tunnel with four bolts. The levelness of linear module can be adjusted by tuning the heights of four nuts. The moving vehicle device is attached to the removable plate, and the skewed winds can be realized by rotating the removable plate (see Fig. 1). More detailed information of moving vehicle device can be found in the reference by Xiang et al. [23].

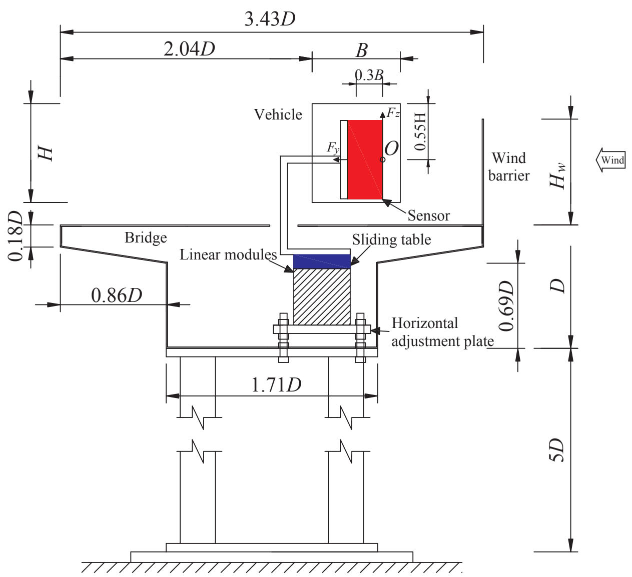

Fig. 1. Cross-sectional schematic of moving vehicle device [23].

The vehicle, wind barrier and bridge model are in the same scale ratio of 1/20. A simplified vehicle model with a cuboid shape is adopted to reduce the effect of Reynolds number, and a six-component force sensor is installed inside the vehicle model. The height, width and length of the scaled vehicle model in a cuboid shape are 0.14 m (H), 0.125 m (B) and 0.52 m (L), respectively. The bridge model is simplified to a simple-supported box girder with auxiliary facilities being ignored. The height, width and length of the scaled bridge model are D (0.175 m), 3.43D, and 54.86D, respectively. The wind barriers made of solid plates in three different heights are installed on the windward edge of the bridge deck to accommodate the free moving of the balance wires on the other side (see Figs. 1 and 2).

A six-component force and moment sensor produced by ATI cooperation is used to measure the aerodynamic forces acting on the vehicle model, which will be used to further derive the aerodynamic coefficients of the vehicle. The six-component balance (version Gamma IP68) has the force range in y-axis as ± 100 N, and those in x- and z-axes as both ± 32 N. The moment in the three directions has a range of ± 2.5 N·m. The precision of the measured force is 0.75%, and the precision of the measured moment is 1.0%. The sampling frequency of the six-component dynamometric balance is 1 kHz.

The acceleration and deceleration durations of the vehicle model are determined by the load inertia and rotor inertia of the servo motor. Based on some preliminary analyses of the weights of vehicle model and sensors [23], the acceleration and deceleration time are both set as 0.8 s. The raw data collected from the experiments are filtered by a low-pass filter with a cut-off frequency of 10 Hz and average processed. The aerodynamic data in the uniform motion state are extracted to derive the aerodynamic coefficients. The schematic diagram of aerodynamic forces and moments is shown in Fig. 3. The F_y-F_z plane located at the L/2 section of vehicles, but the origin of coordinate has a bias which is away from centroid of vehicle (see Fig. 1). Because the scale ratio of angles will be 1.0 regardless of the magnitude of geometric scale ratio, the aerodynamic coefficients of the vehicle model can usually be