Journal of Wind Engineering & Industrial Aerodynamics 177 (2018) 92–100

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

An experimental analysis of the aerodynamic characteristics of a high-speed train on a bridge under crosswinds

Ming Wang [a,b], Xiao-Zhen Li [a,b,*], Jun Xiao [a,c], Qi-Yang Zou [a], Hai-Qing Sha [a]

[a] Department of Bridge Engineering, Southwest Jiaotong University, 610031, Chengdu, Sichuan, China
[b] MOE Key Laboratory of High-Speed Railway Engineering, Southwest Jiaotong University, 610031, Chengdu, Sichuan, China
[c] School of Civil Engineering, Chongqing Jiaotong University, 400074, Chongqing, China

A R T I C L E I N F O

Keywords:
Aerodynamic characteristics
Moving train
Truss bridge
Wind tunnel test
CFD simulation

A B S T R A C T

The aerodynamic characteristics of a train on a bridge under crosswinds are studied by using a wind tunnel. The tests performed measure the aerodynamic forces associated with the model train running inside a truss bridge for different incoming wind velocities, wind angles, and train speeds. For a deeper analysis of the shielding effect of the truss bridge on the train body under crosswinds, a dynamic mesh method is adopted to establish a three-dimensional computational fluid dynamics model. Then the pressure distribution on the surface of the train was analyzed. The results show that the aerodynamic coefficients of the train measured with an equivalent static train model are different to those measured with the dynamic train model. Due to the shielding effect of the truss bridge, the relationships between the aerodynamic coefficients and the yaw angle change with different incoming wind velocities and wind angles. The impact of the train speed on the aerodynamic characteristics is mainly related to changes in the train-induced wind. It leads to the relationship curves between the aerodynamic coefficients and the yaw angle obtained by adjusting the train speed are very different to those by changing the incoming wind velocity and wind angle.

1. Introduction

With the trend of ever higher speeds in public transportation systems, the safety and stability of high-speed vehicles such as trains are of vital importance. One of the most critical problems connected with the safety of running trains is the aerodynamic loads introduced by crosswinds (Cooper, 1981; Tian, 2006; Diedrichs et al., 2007; Bocciolone et al., 2008). A train traveling subject to a crosswind is surrounded by a complex flow field that varies both temporally and spatially. This flow field leads to a variety of aerodynamic forces on the vehicle that ultimately govern its safety (Dorigatti et al., 2015). More complicated vehicle wind environments are produced inside bridges, such as long-span rail-road bridges with truss structures as the main beam, and these wind environments have an impact on the aerodynamic characteristics of the high-speed vehicles. Evaluating the aerodynamics of vehicles subjected to these kinds of wind environments is crucial to the safe operation of modern high-speed vehicles.

Li and Qiang (2002) and Li et al. (2008) have studied the current research situation and the development of vibrations in coupled bridge-vehicle systems, and have emphasized the necessity of studying the operational stability of vehicles under special loads, such as wind loads. Theoretical studies and analyses of coupled wind-vehicle-bridge systems, considering the influence of wind environments, were conducted by Xu et al. (2004), Li et al. (2005), and Han et al. (2014). The purpose of these studies is to develop a more systematic understanding of the operational safety of coupled bridge-vehicle systems subjected to complicated wind environments. The results of such experiments provide important guidance for engineering practice. In the coupled wind-train-bridge systems mentioned above, to acquire the dynamic response of the vehicle and assess its operational stability, the normal approach is to input the aerodynamic characteristics of the vehicle in the form of an external load into the coupled train-bridge system. In such systems, the vehicle aerodynamic characteristics are given by a series of non-dimensional coefficients. One important piece of information that is required for such a calculation is the variation in the aerodynamic side and lift force coefficients and the rolling moment coefficient with the direction of the wind relative to the train — the yaw angle (Baker et al., 2004; Li et al., 2005). The scaled-down wind tunnel test is still the main method used to obtain the aerodynamic coefficients of trains in train-bridge systems, as opposed to computational fluid dynamics (CFD)

* Corresponding author. Department of Bridge Engineering, Southwest Jiaotong University, 610031, Chengdu, Sichuan, China.
E-mail addresses: xzhli@swjtu.edu.cn (X.-Z. Li), jun.xiao@my.swjtu.edu.cn (J. Xiao).

https://doi.org/10.1016/j.jweia.2018.03.021
Received 23 January 2018; Received in revised form 19 March 2018; Accepted 20 March 2018

numerical simulations. Previous studies (Baker and Robinson, 1990; Gawthorpe, 1994; Schetz, 2001; Li and Ge, 2008; Dorigatti et al., 2012; Zhu et al., 2012) tested the aerodynamic coefficients of vehicles in combined train-bridge systems with wind tunnel experiments using train-bridge sectional models.

It is worth mentioning that, for the tests cited above, equivalent simulations with static trains were adopted, neglecting the relative motion between the vehicle and the bridge. Some authors (Schetz, 2001; Bocciolone et al., 2008; Dorigatti et al., 2015) have pointed out that this method is insufficient for simulating the aerodynamic forces of a moving train as it ignores changes in the motion of the train. Some authors (Dorigatti et al., 2015; Premoli et al., 2016) have indicated that the static sectional model is inherently incapable of reproducing the actual skewed wind profile seen by a moving train. Hence, by neglecting the movement of the vehicle, the actual yaw angle perceived by a traveling train can be correctly replicated only at one (reference) height, and there is a mismatch in the vertical profiles of the magnitude and orientation (i.e., the yaw angle) of the relative mean wind velocity. Sterling et al. (2010) demonstrated that while it is possible to obtain agreement with respect to the side force and rolling moment coefficients using a variety of modeling approaches, the lift force coefficient (which is highly affected by the flow near the ground and under the vehicle) is somewhat more problematic. Therefore, considering the difficulties in simulating a realistic underbody flow, it can be hypothesized that a systematic approximation might affect the aerodynamic coefficients obtained through static model experiments (Baker, 1991a; Baker and Humphreys, 1996). Additionally, some previous studies (Suzuki et al., 2003; Bocciolone et al., 2008; Dorigatti et al., 2015) have demonstrated the problem that, while simulating the aerodynamic characteristics of the train, the static sectional model differs from the moving model because the relative wind speed and wind angle (yaw angle β) on the vehicle is the result of the sum of the vectors of the train speed and crosswind, while the infrastructure, being still, is subjected only to the wind velocity in the incoming wind direction, as shown in Fig. 1 (A and B). u represents the mean crosswind velocity in the wind direction, v is the train speed, V_{res} is the velocity relative to the train, α is the angle that the crosswind makes with the direction of travel, and β is the yaw angle, i.e., the angle between the wind velocity and the direction of travel. There have been studies on the differences in aerodynamic forces between static models and moving models (Bocciolone et al., 2008; Dorigatti et al., 2015). But these mainly focus on trains running on flat ground, and the results for these cases show that there is no distinct difference between the aerodynamic forces of the two models. Some studies (Diedrichs et al., 2007; Schober et al., 2010; Cheli et al., 2010) indicate that the larger the infrastructure, compared to the train dimensions, the larger the effect that its interaction with the wind may produce on the train aerodynamics. This usually happens when viaducts are considered. For structures like a steel truss framework, the flow perturbation created by the bridge structure would be expected to be significant (Suzuki et al., 2003; Xiang et al., 2017). When simulating the aerodynamic forces of a vehicle, including interaction with such a bridge, this effect becomes apparent.

To enable aerodynamic information to be reliably obtained for a high-speed train running on a bridge, a scale model experiment has been carried out for a number of vehicle operation cases. The effect of train motion on the aerodynamic force coefficients was considered. This paper presents the results from this investigation. Brief details of the experiment are set out in Section 2. In Section 3.1, differences between the static and moving experiments are observed in the derived aerodynamic coefficients on the middle of the train model. Section 3.2 presents the aerodynamic coefficients of the train model under different incoming wind velocities. The effect of the wind angle on the aerodynamic coefficients of the train is described in Section 3.3. With the help of computational fluid dynamics (CFD) simulations, the pressure distribution and the pressure coefficients of the train model are also presented. The intention is to explain the differences in the aerodynamic characteristics of the train model with different wind angles. Section 3.4 summarizes the effects of wind environment variation on the aerodynamic coefficients of the train. Finally, appropriate conclusions are drawn in Section 4.

2. Experimental setup

The tests were carried out in the XNJD-3 36.0 m × 22.5 m × 4.5 m environmental wind tunnel at Southwest Jiaotong University in China. A steel-truss bridge and a CRH3 train system are fabricated with a scale ratio of 1:30 for aerodynamic tests of the high-speed trains. The moving model test system was composed of a model train, a model bridge, the drive system, and the data collection system. The test topography is shown schematically in Fig. 2. For comparison with previous moving vehicle model devices (Baker, 1986; Humphreys, 1995; Li et al., 2014; Xiang et al., 2017), the model was 20.5 m in length and 1.57 m in height, with a maximum running distance of 18 m. The improvements made to the device used in this paper were mainly in the drive mode and data collection system. Firstly, servo-motors and synchronizer wheels were installed on each side of the linear guide rail to cooperate with the timing belt and the sliders in the linear guide to form a closed-loop driving system. The power of the system was provided by a 4 kW servo-motor. This provides sufficient power to achieve acceleration and deceleration over short distances with bidirectional motion, rather than affecting the acceleration and deceleration performance. The maximum vehicle speed was 15 m/s. The train model contained three cars: a head car, a middle car, and a tail car. To reduce the effects of the open slots, as shown in Fig. 2 (b), bias connectors are used to connect the three train bodies to the sliders and keep them away from the open slot on the guideway (Baker, 1986; Howell, 1986). Secondly, the data collection system adopted ATI's Mini 40 wireless transducer modules. This can help by avoiding towline problems caused by using wired balance sensors (Baker, 1986; Li et al., 2014; Xiang et al., 2017). In addition, the linear guideway was separated from the bridge model to keep the movement of the train model as smooth as possible. With these improvements, the system could be applied not only to aerodynamic tests of vehicles on bridges, but also to tests of trains in other complex operating environments, such as near or

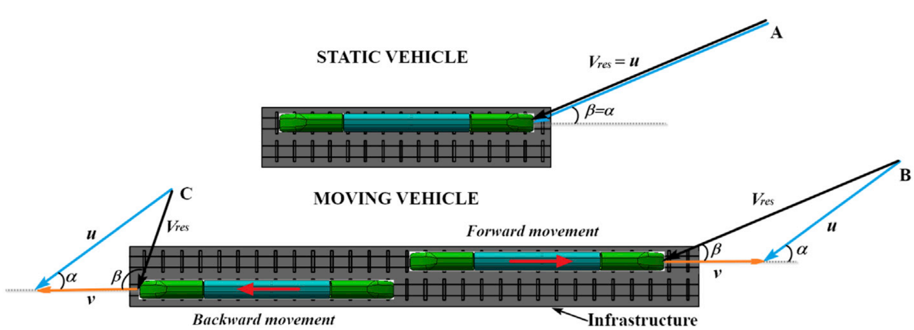

Fig. 1. Velocity triangles: moving vs static vehicle simulations.