

Wind tunnel measurements of aerodynamic forces on vehicles and bridges under crosswinds

Yan Han^a, Steve C. S. Cai^{b,a}, Zhengqing Chen^c, Jiexuan Hu^a, Chunguang Li^a

^a*School of Civil Engineering and Architecture, Changsha University of Science & Technology, Changsha, Hunan, China, 410004*

^b*Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, USA, LA 70803*

^c*Wind Engineering Research Center, College of Civil Engineering, Hunan University, Changsha, Hunan, China, 410082*

ABSTRACT: An accurate identification of the aerodynamic characteristics of vehicles and the corresponding bridge is the premise for the coupling vibration analysis of the wind-vehicle-bridge system. At present, the interaction of aerodynamic forces between the road vehicles and bridge is ignored in most researches. In the present study, an experimental setup was made to measure the aerodynamic characteristics of vehicles and the bridge for different cases in a wind tunnel considering the aerodynamic interference. The influence of the wind turbulence, the wind speed, the vehicle interference, and the distance of vehicle from the windward edge of the deck on the aerodynamic coefficients of vehicles, and the influence of vehicles on the static coefficients of the bridge were investigated based on the experimental results. The change reasons of the aerodynamic characteristics of vehicles and the bridge were attempted to be researched and the reliability of the measured results was validated according to the results of surface pressure of the vehicle and the bridge. The measured results showed that the wind turbulence, the vehicle interference, and the vehicle distance from the windward edge significantly affected the aerodynamic coefficients of vehicles. However, the influence of the wind speed on the aerodynamic coefficients of the studied vehicle is small. The static coefficients of the bridge were also significantly influenced by the presence of vehicles.

KEYWORDS: wind-vehicle-bridge system; cross winds; aerodynamic characteristics; aerodynamic interference; wind tunnel tests; numerical simulation.

1 INTRODUCTION

Economic and social developments increase tremendously the traffic volume over bridges and roads. Heavy road vehicles on bridges may significantly change the local dynamic behavior and affect the fatigue life of the bridge. On the other hand, the vibrations of the bridge under cross winds also in turn affect the safety of the road vehicles. These inevitably increase the potential risk of road vehicles moving on a bridge and subjected to strong winds. Thus, it is important to study the dynamic interaction between the bridge, road vehicles, and wind loads for ensuring the safety and normal working performance of both the road vehicles and bridge. Most existent research works focus on either wind action on vehicles running on roadway (Baker, 1986; 1987; 1988; 1991a,b), wind effect on the bridge without considering vehicles (Scanlan, 1990), or vehicle-bridge interaction analysis without considering wind effect (Yang, 1997; Pan, 2002).

For exactly estimating the response of a bridge and the safety of the vehicles moving on the bridge under cross winds, it is necessary to establish an analytical framework of vehicle-bridge-wind interaction. This problem has been noticed and studied by researchers in China and abroad. Xu et al. (2003) have investigated the coupled dynamic analysis of road vehicle and cable-stayed bridge system under turbulent wind. Cai et al. (2004) have built a framework for the vehicle-

bridge-wind aerodynamic analysis, which lays a very important foundation for road vehicle accident analysis based on dynamic analysis results and facilitates the aerodynamic analysis of bridges considering vehicle-bridge-wind interaction. Han and Chen (2007) also presented a state of the art three-dimensional dynamic model of the wind-vehicle-bridge coupling vibration. However, the aerodynamic forces on vehicles in previous studies were either built on the work undertaken by Baker [1991a,b] or obtained from wind tunnel tests, which did not consider the interaction of aerodynamic forces between the road vehicles and the bridge.

The aerodynamic force coefficients of vehicles under wind loads depend on not only the shapes of vehicles but also those of infrastructures, such as the bridge. On the other hand, the aerodynamic parameters of the bridge will be influenced by the vehicles on it. Therefore, in order to predict the performance of vehicle-bridge system under wind loads rationally, it is necessary to study the aerodynamic properties of road vehicles and bridges considering the interaction of aerodynamic forces between the road vehicles and the corresponding bridges. There is a wealth of data pertaining to the wind load coefficients for vehicles on standard 'open ground' scenario (Baker, 1991a; Quinn et al., 2007). However, the corresponding data for bridge decks with vehicles is sparse. Coleman and Baker (1990; 1994) measured the load coefficients of an articulated lorry positioned on the bridge deck model. Minoru Suzuki et al. (2003) carried out three kinds of wind tunnel tests to evaluate the aerodynamic characteristics of typical configurations of vehicles on typical configurations of infrastructures such as bridges and embankments. But the load coefficients of the bridge deck model were not presented. Li et al. (2004) developed a separation device, called the Cross Slot System, to measure the aerodynamic characteristics of the rail vehicle-bridge system taking aerodynamic interaction between the rail vehicle and the bridge into account. Diana and co-workers (Diana, 2004; 2006) undertaken much work on the aerodynamic effects of rail vehicles. Though these researches (Li, 2004; Diana, 2004; 2006) aimed at rail vehicles, the method is worth learning for road vehicles. Han et al. (2011) calculated the load coefficients for a car container running on the bridge and the load coefficients for the bridge were also investigated by numerical simulations (CFD).

This paper developed an experiment technique and carried out a series of wind tunnel experiments to examine the aerodynamic characteristics of vehicles and bridge in the HD-2 wind tunnel at Hunan University. All the measurements were undertaken in static conditions (i.e., with no vehicle movement) over a range of yaw angles from 0° ~ 90° . The tests were carried out in both smooth flow and high turbulence flow simulated by a turbulence producing grid.

The experimental set-up adopted for the wind tunnel tests is outlined in Section 2, which illustrates the bridge deck and vehicle geometries and the instrumentation, test conditions and testing procedure, and the characteristics of the simulated wind. Section 3 reports and examines the values of the aerodynamic force/moment coefficients of the vehicle and the bridge corresponding to a variety of configurations tests. More specifically, the six studied cases are presented and compared. Finally, some conclusions are drawn in Section 4. It is found that the wind turbulence, the vehicle interference, and the vehicle distance from the windward edge significantly affected the aerodynamic coefficients of vehicles. However, the influence of the wind speed on the aerodynamic coefficients of the studied vehicle is small. The static coefficients of the bridge were also significantly influenced by vehicles.

2 WIND TUNNEL EXPERIMENTS

The experiment is carried out in the HD-2 wind tunnel of Hunan University that is a low-speed, one-close-circuit medium-sized boundary layer wind tunnel with two parallel test sections.

2.1 Bridge deck and vehicle geometries

The models are made with polymethylmethacrylate and the scale is 1:32. The bridge section model is divided into three parts. The intermediate part is the testing model with a length of 1.04 m. The two terminal parts are the compensation models with a length of 0.5 m, the role of which is to avoid the flow around the end and to improve the test precision. The distance between the intermediate part and the terminal part is 0.005 m. The details and dimensions of the bridge deck section and the vehicle are given in Figs. 1a and 1b. The distance between the bottom of the vehicle and the top surface of the bridge deck is 0.015 m. The distance of the vehicle from the bridge deck windward edge is defined by d with the values of 0.166 m and 0.547 m corresponding to the two different transverse positions of the vehicle on the bridge deck, windward and leeward, as shown in Fig. 1c. Three vehicles are made to investigate the aerodynamic interference between vehicles, which are laid on the bridge deck with an equal distance of 0.156 m between vehicles along the longitudinal direction, as shown in Fig. 1c. The middle vehicle model is the test vehicle and the terminal vehicle models are the interference vehicles.

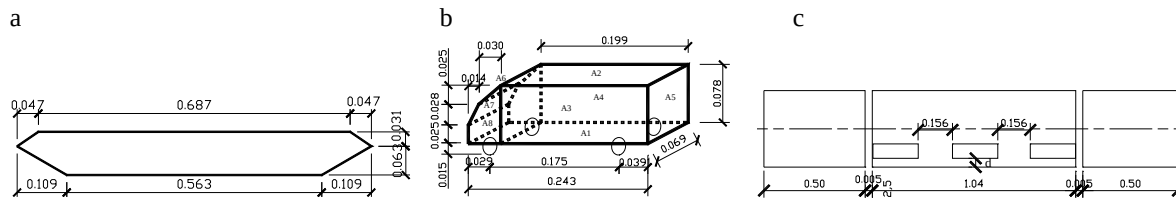


Fig.1 Model geometry and overall dimensions (Unit: m) (a: Bridge cross section model; b: Vehicle model; c: Layout plan of the model)

2.2 Experimental set-up

The experimental set-up is composed of three test frames, the middle test frame and the two end compensation frames, as shown in Fig. 2, each of which is composed of three parts, the upper, the middle, and lower parts. The upper part fixes the model to the test frame by using bolts. The middle part is the circular steel tube with a little smaller diameter, of which the top is connected with the upper part by using bolts and the end is inserted into the circular steel tube of the lower part and fixed with the lantern ring. The lower part is the composite structure of the circular steel tube with a greater diameter and steel bar, which is connected with the rotating table in the wind tunnel by using bolts. In the experimental process, the test frames and the models are rotating with the table together to vary the wind yaw angle.

2.3 Turbulence wind field simulation

A passive turbulence generator was developed for generating homogeneous turbulence wind field, as shown in Fig. 3. The characteristics of the generated flow in the wind tunnel were measured by a TFI Series 100 cobra probes (Turbulent Flow Instrumentation). The turbulence intensity at the deck height was approximately 10% in the flow direction. The longitudinal integral scale for the streamwise velocity was 0.5 m which is well above the vehicle height (or length or width); thus ensuring that the turbulent structures are well correlated over the vehicles.

Fig. 4 indicates the power spectral density of the approaching streamwise velocity. To facilitate a comparison between the wind tunnel simulation and the target spectrum at full scale (i.e., the Von Karman Spectrum) both the axes in Fig. 4 have been non-dimensionalized. The horizontal axis represents the reduced frequency ($\bar{f} = f \cdot L_u / U$) defined by the product of the frequency (f) and the turbulence length scale (L_u), divided by the reference mean wind speed. On the vertical axis the spectrum is multiplied by the frequency and divided by the mean velocity variance. The experimental and target spectra agree qualitatively well over a large proportion of the reduced frequency range, which suggests that the turbulence simulation is sufficient for the current purposes.

2.4 Force measurements

The forces on the bridge and the vehicle were determined by integrating the pressure of the pressure taps measured using electronically scanning pressure measurement system. The bridge model was installed with 329 pressure-taps, mounted flush with the surfaces of the bridge model and connected to the pressure transducers via flexible tubing. Seven pressure-tapped strips were located along the span of the bridge deck, as shown in Fig. 5a, to take into account the span-wise correlation of the aerodynamic forces. Each pressure-tapped strip has 47 pressure-taps representing the surface pressure distributions, as shown in Fig. 5b. The vehicle model was installed with 200 pressure-taps, as shown in Fig. 6. Figs. 7 and 8 outline the sign conventions for aerodynamic forces of the bridge and the vehicle, respectively.



Fig. 2 Experimental setup



Fig. 3 Passive grid device

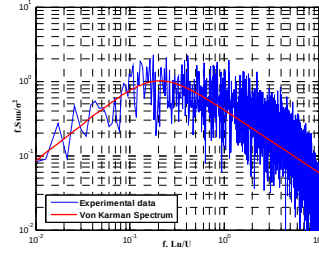


Fig. 4 Power spectral density of wind field

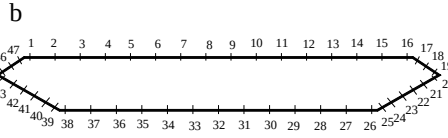
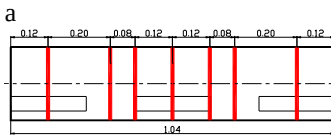


Fig. 5 The sketch map of pressure taps of the bridge cross section: (a) The positions of seven pressure-tapped strips (dimensions in meters); (b) The positions and notions of pressure-taps for each pressure-tapped strip

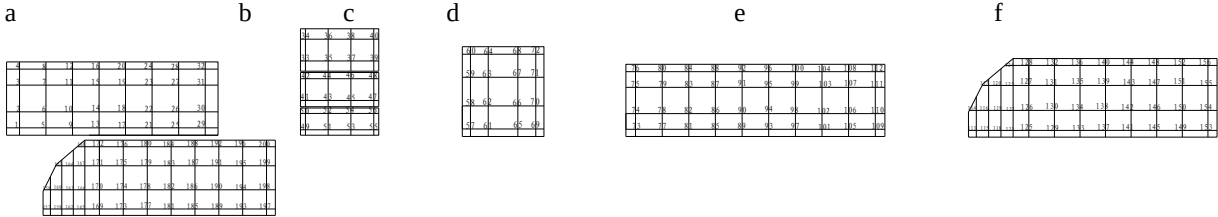


Fig. 6 The positions and notions of pressure-taps for each surface of the vehicle: (a) Top surface; (b) Frontal surface; (c) Back surface; (d) Bottom surface; (e) Left side surface; (f) Right side surface

The instantaneous fluctuating surface pressure at time t in a particular strip ($j=1-7$) were integrated independently over each of the seven pressure-tapped strips. The lift force $F_{Vj}(t)$, drag force $F_{Hj}(t)$ and the pitching moment $M_j(t)$ per unit span length of the bridge deck were calculated according to Equations (1a), (1b) and (1c), respectively, as:

$$F_{Vj}(t) = \sum_{i=1}^{47} p_{ij}(t) \Delta A_{ij} \cos(\alpha_{ij}) \quad (1a) \quad F_{Hj}(t) = \sum_{i=1}^{47} p_{ij}(t) \Delta A_{ij} \sin(\alpha_{ij}) \quad (1b)$$

$$M_j(t) = \sum_{i=1}^{47} p_{ij}(t) \Delta A_{ij} d_{Hij} \sin(\alpha_{ij}) + \sum_{i=1}^{47} p_{ij}(t) \Delta A_{ij} d_{Vij} \cos(\alpha_{ij}) \quad (1c)$$

where $p_{ij}(t)$ = the instantaneous fluctuating surface pressure of the bridge at time t ; ΔA_{ij} = the tributary area of a pressure-tap of the bridge; α_{ij} = angle between the local (pressure-tap) and vertical axis; and d_{Hij}, d_{Vij} = pitching moment arms about the centre of the bridge deck.

The instantaneous fluctuating surface pressures at time t were integrated independently over each surface of the vehicle. The side force $F_S(t)$, lift force $F_L(t)$, drag force $F_D(t)$, pitching moment $F_P(t)$, yawing moment $F_R(t)$, and rolling moment $F_R(t)$ of the vehicle were calculated according to Equations (2a), (2b) and (2c), respectively, as:

$$F_S(t) = \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Si} \quad (2a) \quad F_L(t) = \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Li} \quad (2b) \quad F_D(t) = \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Di} \quad (2c)$$

$$F_P(t) = \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Li} d_{(L-S)i} + \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Di} d_{(D-S)i} \quad (2d)$$

$$F_Y(t) = \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Si} d_{(S-L)i} + \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Di} d_{(D-L)i} \quad (2e)$$

$$F_R(t) = \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Li} d_{(L-D)i} + \sum_{i=1}^{200} p_i(t) \Delta A_i \Theta_{Si} d_{(S-D)i} \quad (2f)$$

where $p_i(t)$ = the instantaneous fluctuating surface pressure of the vehicle at time t ; $\Delta A_i(t)$ the tributary area of a pressure-tap of the vehicle; Θ_{Fi} ($F = S, L, D$) = the decomposition coefficients of surface pressure along the direction of side, lift, or drag force; $d_{(L-S)i}$ and $d_{(D-S)i}$ = horizontal moment arms of lift force and vertical moment arm of drag force contributing to the pitching moment, respectively; $d_{(S-L)i}$ and $d_{(D-L)i}$ = horizontal moment arms of side force and horizontal moment arm of drag force contributing to the yawing moment, respectively; $d_{(S-D)i}$ and $d_{(L-D)i}$ = vertical moment arm of side force and horizontal moment arms of lift force contributing to the rolling moment, respectively.

Based on the integrated lift force, drag force, and pitching moment, the corresponding force and moment coefficients of the bridge were determined according to Equations (3a), (3b) and (3c), respectively, as:

$$C_{F_H} = \frac{1}{7} \sum_{j=1}^7 \frac{\bar{F}_{Hj}}{0.5 \rho U^2 B} \quad (3a) \quad C_{F_V} = \frac{1}{7} \sum_{j=1}^7 \frac{\bar{F}_{Vj}}{0.5 \rho U^2 B} \quad (3b) \quad C_M = \frac{1}{7} \sum_{j=1}^7 \frac{\bar{M}_j}{0.5 \rho U^2 B^2} \quad (3c)$$

where ρ = the air density; U = the mean wind speed on the elevation of the bridge; $\bar{F}_{Hj}$, $\bar{F}_{Vj}$ and $\bar{M}_j$ = the time averaged values of the lift force, drag force, and pitching moment in equations (1a), (1b) and (1c) over the required time period for Strip j ; and B = the width of the bridge deck.

Based on the integrated side force, lift force, drag force, pitching moment, yawing moment, and rolling moment, the corresponding force and moment coefficients of the vehicle were determined according to Equations (4a)-(4f), respectively, as:

$$C_S(\psi) = \frac{\bar{F}_S}{0.5 \rho V^2 A} \quad (4a) \quad C_L(\psi) = \frac{\bar{F}_L}{0.5 \rho V^2 A} \quad (4b) \quad C_D(\psi) = \frac{\bar{F}_D}{0.5 \rho V^2 A} \quad (4c)$$

$$C_P(\psi) = \frac{\bar{F}_P}{0.5 \rho V^2 Ah} \quad (4d) \quad C_Y(\psi) = \frac{\bar{F}_Y}{0.5 \rho V^2 Ah} \quad (4e) \quad C_R(\psi) = \frac{\bar{F}_R}{0.5 \rho V^2 Ah} \quad (4f)$$

where $\bar{F}_S$, $\bar{F}_L$, $\bar{F}_D$, $\bar{F}_P$, $\bar{F}_Y$ and $\bar{F}_R$ = the time averaged values of the side force, lift force, drag force, pitching moment, yawing moment, and rolling moment in equations (2a)-(2f) over the required time period; A = frontal area of the vehicle; h is the distance from the gravity center of the vehicle to the road surface; and V is the relative wind speed to the vehicle, of which the specification is shown in Fig. 9.

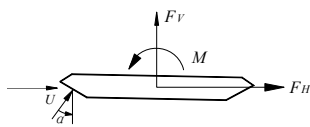


Fig. 7 Sign convention for aerodynamic forces of the bridge

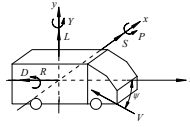


Fig. 8 Sign convention for aerodynamic forces of the bridge

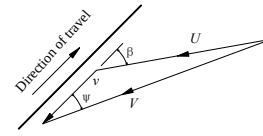


Fig. 9 Velocities and directions

In Fig. 9, v is the vehicle speed; ψ is the relative wind yaw angle to the vehicle; β is the angle between the wind direction and the vehicle direction of travel, and $\psi = \beta$ in this paper.

2.5 Test configurations and experimental procedure

Table 1 outlines the experimental configurations examined in the current work. In order to vary the yaw angle for the vehicle, the bridge and vehicle were simply rotated with respect to the on-coming wind together with the test frame and the rotating table in the wind tunnel. Seven yaw angles of 0° , 15° , 30° , 45° , 60° , 75° and 90° were investigated. To investigate the influence of wind velocity, two velocities of 10 m/s and 20 m/s were adopted. Three vehicles were laid on the bridge deck with an equal distance of 0.156 m between the vehicles along the longitudinal direction to investigate the aerodynamic interference between the vehicles. The tests were carried out in smooth flow and turbulent flow with approximately 10% turbulence intensity described in Section 2.3. The local wind field of the surface of the bridge deck is expected to be modified as a result of the vehicle. Also, the local wind field of the vehicle is expected to be modified as a result of the bridge. Then, the vehicle model was positioned at two different locations corresponding to windward and leeward lanes.

Table 1 Measured cases in wind tunnel

Cases	Testing objects	Wind Velocity (m/s)	Wind field	Distance (d) of vehicle from the wind ward edge of the deck (m)	Wind yaw angle ($^\circ$)
1	Bridge with one vehicle	10	Smooth	0.166	0, 15, 30, 45, 60, 75, 90
2	Bridge with one vehicle	20	Smooth	0.166	0, 15, 30, 45, 60, 75, 90
3	Bridge with one vehicle	10	Smooth	0.547	0, 15, 30, 45, 60, 75, 90
4	Bridge with one vehicle	10	Turbulent	0.166	0, 15, 30, 45, 60, 75, 90
5	Bridge with three vehicles	10	Smooth	0.166	0, 15, 30, 45, 60, 75, 90
6	Bridge with no vehicle	10	Smooth	0	0, 15, 30, 45, 60, 75, 90

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Aerodynamic force coefficients

Figure 10 illustrates the variation of force and moment coefficients of the vehicle with respect to the yaw angle ψ for cases 1 and 5. It can be seen that for case 1, the side force coefficient C_S increases with the increase of the yaw angle ψ and reaches a maximum value at around 90° yaw angle. But the increment between the yaw angles of 60° - 90° is less significant. Such a trend is similar to that shown in the literature (Baker, 1991a; Coleman, 1990), although it is noted that the maximum values typically occur between yaw angles of 60° - 90° . The lift force coefficient C_L increases and then decreases with the increase of the yaw angle ψ , and reaches a maximum value at around 30° yaw angle, which is positive for $15^\circ < \psi < 60^\circ$, and negative for other yaw angles. The positive values (sign convention shown in Fig. 8) of C_L are not good for traffic safety. The magnitude of the drag force coefficient C_D increases to a maximum at $\psi = 30^\circ$ and then decreases to near zero for $\psi = 90^\circ$, i.e. pure cross wind conditions, which seems reasonable. The aerodynamic moments reflect the trends of the aerodynamic forces. The yawing moment coefficient, determined mainly by the horizontal moment arm of the drag force, and to a lesser extent of that of the side force, shows similar variations to those observed in the drag force coefficient. The pitching moment and rolling moment results, relatively small, are changing irregularly, and are probably affected by some unknown experimental error.

In addition, from the comparison of the results for cases 1 and 5 (one vs. three vehicles in Fig. 10), it can be seen that the change trend of the aerodynamic coefficients is similar for the two cases, except for the pitching moment coefficient. The side force coefficient C_S in case 5

with three vehicles is obviously less than that in case 1 with one vehicle for $\psi < 45^\circ$ because of the blocking effect of the frontal vehicle on the middle vehicle, i.e. the test vehicle. When the blocking effect is not obvious for $\psi > 45^\circ$, the side force coefficient C_S for case 5 is slightly larger than that in case 1 due to the effect of the frontal and posterior vehicles on the surrounding flow field. There is a obvious difference in the lift force coefficient C_L between cases 1 and 5, especially for 30° yaw angle, at which the lift force coefficient C_L for case 5 is obviously less than that in case 1, which means the effect of frontal and posterior vehicles is good for traffic safety. The frontal vehicle affects the drag force coefficient C_D greatly, which reduces the magnitude of the drag force coefficient C_D , especially for $\psi < 60^\circ$. The magnitudes of the pitching moment coefficient C_P and the yawing moment coefficient C_Y for case 5 are less than those in case 1, while the rolling moment coefficient C_R is generally larger (in absolute values) due to the interference of frontal and posterior vehicles.

Figure 11 illustrates the variation of the aerodynamic force coefficients of the vehicle with respect to yaw angle ψ for cases 1 and 4 (smooth vs. turbulent flow). It can be seen that the side force coefficient C_S for turbulent flow is smaller than that in the smooth flow and the difference increases with the increase of the yaw angle. The turbulence effects on the lift force coefficient C_L is not obviously for low yaw angles. For $\psi > 40^\circ$, the lift force coefficient C_L in turbulent flow is significantly greater than that in the smooth flow case. The magnitude of the drag force coefficient C_D for the turbulent flow is smaller than that in the smooth flow for $\psi < 45^\circ$, and slightly greater for $\psi > 45^\circ$. The turbulence reduces the yawing moment basically and affects the pitching and rolling moment irregularly.

A further investigation on the influence of the distance of the vehicle from the windward edge of the deck on the aerodynamic force coefficients is illustrated in Figure 12 which shows the evolution of the aerodynamic coefficients with respect to the two distances (i.e., $d=0.166$ m and 0.547 m corresponding to cases 1 and 3). For $\psi < 30^\circ$, there is a good agreement between the results of the side force coefficient C_S in the two cases. But the increase of the distance reduces C_S greatly for $\psi > 30^\circ$. At zero degree yaw angle, the lift force coefficient C_S is not affected by the distance. But it decreases with the increase of distance d for $\psi < 40^\circ$, and increases for $\psi > 40^\circ$. The increase of the distance increases the magnitude of the rolling moment coefficient C_R for all yaw angles, except for 30 degree. The changing of the distance affects the drag force, pitching moment, and yawing moment coefficients insignificantly.

Figure 13 shows the variation of the aerodynamic force coefficients of the vehicle with respect to the yaw angle ψ for cases 1 and 2 (10 vs. 20 m/s wind velocity) to investigate the effect of the wind speed on the coefficients. It can be seen that there is very little difference between the results for all the aerodynamic force coefficients, which is perhaps not surprising since the vehicle model has sharp windward edges. As a result, the coefficients will be little affected by the Reynolds number (i.e. the wind velocity here).

Table 2 gives the static aerodynamic force coefficients of the bridge for cases 6, 1, 5 and 3 at the 90° yaw angle. The results show that the aerodynamic force coefficients of the bridge are affected by the vehicles greatly, especially for lift force coefficient C_V , which increases significantly with the increase of the vehicle number. The drag force coefficient C_H with one vehicle is obviously greater than that with no vehicle, but little smaller than that with three vehicles, which indicates the drag force coefficient C_H is independent of the number of vehicles. The magnitude of the pitching moment coefficient C_M with three vehicles is significantly greater than that with one vehicle or with no vehicle, but there is little difference between the results with one vehicle and with no vehicle. The distance of the vehicle from the windward edge of the bridge deck affects the aerodynamic force coefficients of the bridge greatly. It not only affects the magnitude but also the direction.

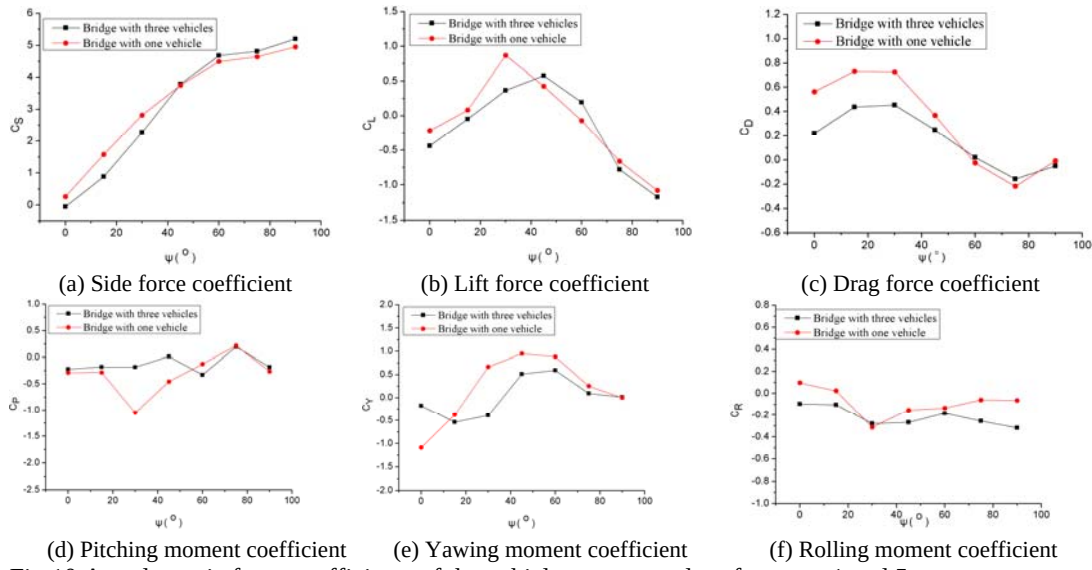


Fig.10 Aerodynamic force coefficients of the vehicle vs yaw angle ψ for cases 1 and 5

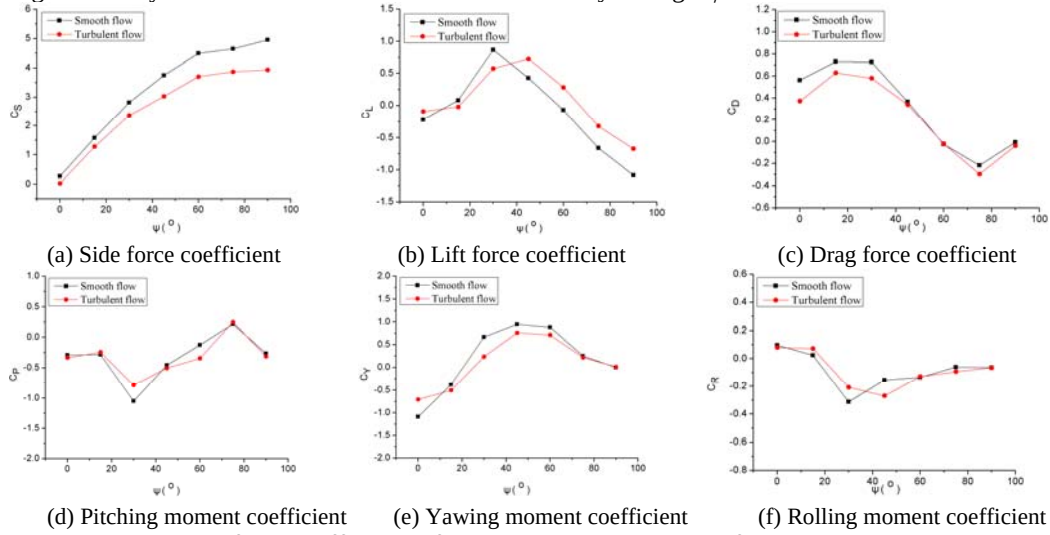


Fig.11 Aerodynamic force coefficients of the vehicle vs yaw angle ψ for cases 1 and 4

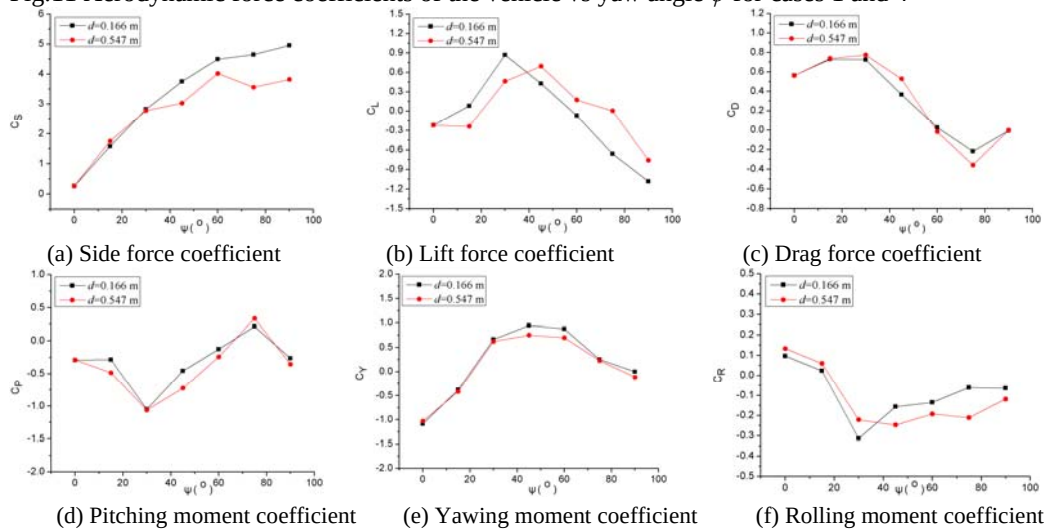


Fig.12 Aerodynamic force coefficients of the vehicle vs yaw angle ψ for cases 1 and 3

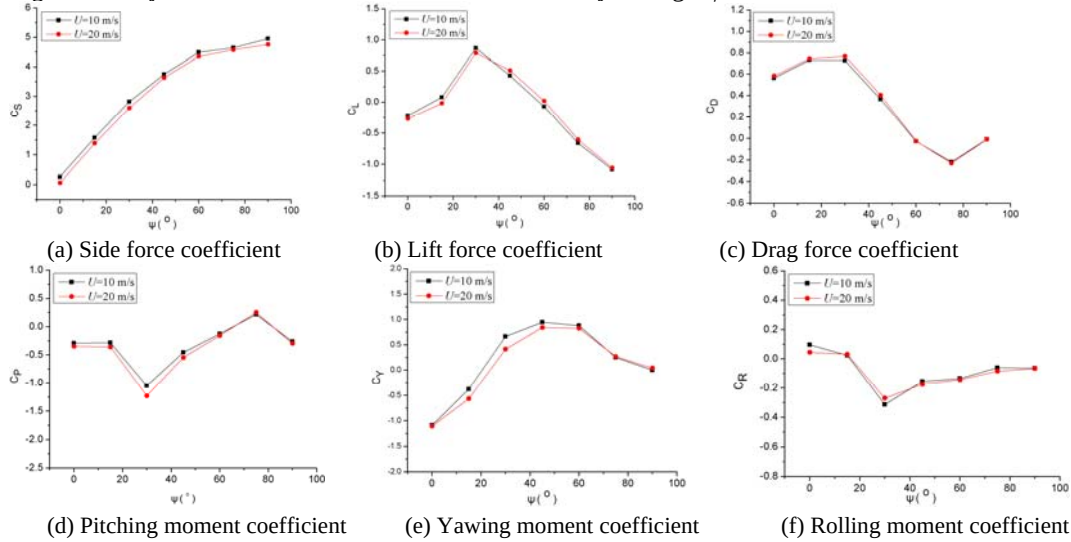


Fig.13 Aerodynamic force coefficients of the vehicle vs yaw angle ψ for cases 1 and 5

Table 2 Static coefficients of the bridge

Coefficients	With no vehicle	With one vehicle ($d=0.166$ m)	With three vehicle ($d=0.166$ m)	With one vehicle ($d=0.547$ m)
C_V	0.1486	0.2602	0.3287	-0.0983
C_H	0.0583	0.0669	0.0672	-0.0830
C_M	-0.0175	-0.0141	-0.0341	0.0445

3.2 Pressure distribution

A further investigation on the change reasons of the aerodynamic forces for the vehicle and the bridge is illustrated in the following figures, showing the surface pressure distribution of the vehicle and the bridge. Figure 14 gives the pressure contour maps of the windward side surface of the vehicle at the 90° yaw angle for cases 1, 4, 5 and 3. Figure 15 gives the pressure contour maps of the frontal surface of the vehicle at the 0° yaw angle for cases 1 and 5. Figure 16 shows the pressure distribution of the top pressure taps of the middle strip of the bridge deck at the 90° yaw angle for cases 1, 3, 5 and 6. It can be seen from these figures that there are no abnormal values for all pressure taps, demonstrating the accuracy and reliability of the experimental results.

From Figures 14(a) and 14(c), it can be seen that there is a good agreement between the pressure contour maps, which verifies that the effect of the frontal and posterior vehicles on the side force coefficient C_S is not obvious, just as shown in Figure 10(a). By comparing Figure 14(a) with Figure 14(b), it can be seen that the pressure for case 4 is obviously smaller than that in case 1, which explains the decrease of the side force coefficient C_S in turbulence flow at the 90° yaw angle, as shown in Figure 11(a). Though the pressure in case 3 is not smaller than that in case 1, as illustrated in Figures 14(a) and 14(d), the high pressure area becomes small, which decreases the side force coefficient C_S at the 90° yaw angle obviously, as shown in Figure 12(a).

As illustrated in Figures 15(a) and 15(b), the pressure in case 5 is obviously smaller than in case 1 for the blocking effect of the frontal vehicle, which is the main reason for the obvious decrease of the drag force coefficient C_D at the 0° yaw angle, as shown in Figure 10(c).

From Figure 16, it is observed that for case 6 (with no vehicle), the pressure is negative, that is, the measured point is subjected to a tensile force with an upward direction (i.e. the positive direction of lift force). The pressure increases (the absolute value decreases) with the increase of the distance from the windward edge and then basically remains unchanged after the

distance is up to a certain value. For case 1 (one vehicle with $d=0.166m$), the pressure of the measured point located in front of the vehicle on the windward side increases sharply with the increase of the distance due to the blockage effect of the vehicle, changing from negative to positive. The pressure turns to be negative when the measured point is located under the vehicle and approaches to the value like that in case 6. The magnitude of the pressure for case 1 is larger than that in case 6 with the direction upward, which leads to the lift force coefficient C_V to change correspondingly. For case 5 (with three vehicles), the variation of the pressure is similar to that in case 1, except for the pressure taps in front of the windward side of the vehicle. Since there are three strips of the bridge deck (as shown in Figure 3(a)) affected by the vehicles, the lift force coefficient C_V in case 5 is obviously higher than that in case 1. For case 3 (one vehicle with $d=0.547m$), the pressure increases with the increasing of the distance, turns from negative to positive, but decreases sharply near the vehicle and becomes negative. There are half measured points that have positive pressure values with a downward direction. As a result, the lift force coefficient C_V in case 3 is negative and is lower than that in case 6. From the above analysis, it is not hard to understand the change reason of the lift force coefficients presented in table 2.

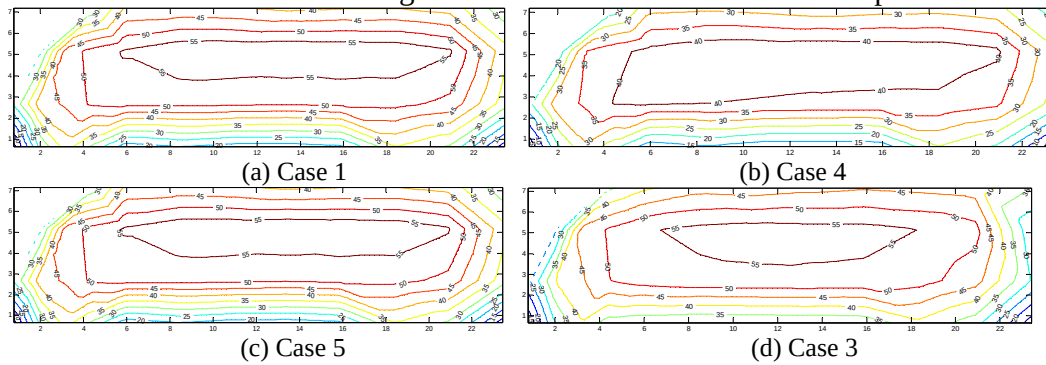


Fig.14 Pressure contour map of the windward side surface of the vehicle at 90° yaw angle

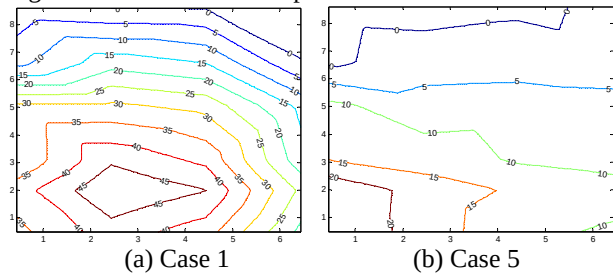


Fig.15 Pressure contour map of the frontal surface of the vehicle at 0° yaw angle

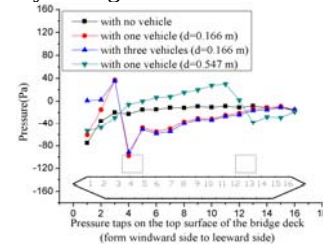


Fig.16 The pressure of top pressure taps of the middle strip

4 CONCLUSIONS

The present work has investigated the aerodynamic force coefficients of the vehicle and the bridge by carrying out six experimental tests in wind tunnel. Based on the experimental results, the following conclusions can be drawn:

(1) The analysis of surface pressure distributions of the vehicle and bridge proves that experimental results in this paper are accurate and reliable.

(2) The aerodynamic coefficient is obviously a function of the yaw angle. The side force coefficient C_S increases with the increase of the yaw angle ψ , the lift force coefficient C_L increases and then decreases with the increase of the yaw angle ψ , the drag force coefficient C_D increases and then decreases with the increase of the yaw angle ψ , the yawing moment coefficient shows similar variations to those observed in the drag force coefficient, and the pitching moment and rolling moment results are relatively small.

(3) The interference of vehicles, the flow turbulence, and the cross position of vehicles largely affect the aerodynamic force coefficients of vehicles, but the wind velocity basically has no influence on these coefficients. The effects of the number of vehicles and the distance of vehicles from the windward edge on the aerodynamic force coefficients of bridges are strong. When there is a vehicle or no vehicle on the bridge, the aerodynamic force coefficients of the bridge is largely affected, just as do the number of vehicles and the distance of vehicles from the windward edge.

(4) There are still many factors that may affect the aerodynamic force coefficients of the vehicle, such as the configuration of the bridge cross section, the vehicle type, and the running environment (on bridge, embankment, or ground). These factors should be studied to develop empirical formulas to calculate the aerodynamic forces for typical vehicles.

(5) It is known that vehicles on bridges have significant effect on the static aerodynamic forces of the bridge. How much effect of the vehicle on other aerodynamic forces of the bridge, such as the self-excited force and buffeting force, and on the wind-induced vibrations of the bridge is worth a further study.

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