中國機械工程學刊第四十卷第二期第 171~178 頁(民國一百零八年)
Journal of the Chinese Society of Mechanical Engineers, Vol.40, No.2, pp 171~178 (2019)

Study on the Difference of Vehicle Aerodynamic Characteristics Between Static and Dynamic Analysis Models

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Keywords: wind-vehicle-bridge system; coupling vibration; aerodynamic parameters; travel safety; numerical simulation

ABSTRACT

The issues with coupling vibrating of the wind-vehicle-bridge system are related to not only vehicle ride comfort but also driving safety. Static vehicle-bridge model and dynamic vehicle-bridge model are built up respectively and the aerodynamic coefficients as a function of wind direction are analyzed. Then based on the analysis results from the static numerical wind tunnel simulation and dynamic numerical wind tunnel simulation, the overturning and sideslip critical wind speeds of vehicle running at different speeds on dry, wet, snow, icy road conditions under different yaw angles wind action were calculated respectively. Results show that, while vehicle running on the bridge, it should consider the interaction between the vehicle-bridge system and natural wind to study the aerodynamic characteristics of vehicle and driving safety. While vehicle running on a long-span bridge under different yaw angles wind excitation, it is not safe to take safety critical wind speeds under cross wind excitation as safety critical wind speeds.

INTRODUCTION

The factors such as rain, snow, wind and other bad weather are the major cause of affecting the expressway traffic accidents. It is estimated that 50% of traffic accidents in China are caused by the bad weather. Among the traffic accidents occurred in the adverse weather, 71% are serious traffic accidents and the direct economic loss from traffic accidents is 65% (Xiao Zhuo 2013). While vehicle running on a bridge under wind action, driving safety analysis requires comprehensive consideration of interaction between the vehicle-bridge system and natural wind environment (LI Xiao-zhen et al. 2008).

The wind-vehicle-bridge system is regarded as a coupled mechanical system consisted of wind action, vehicles and bridge with coordinate interaction. When vehicles running on the bridge under the wind action, vehicles and bridge subjected to wind excitations. At the same time, the vibration of the vehicle-bridge system leads the variation of natural wind field characteristics around which will lead the change of the aerodynamic force acting on bridge and vehicles.

Currently, there are two major methods used in investigating vehicle aerodynamic characteristics, wind tunnel test (LI Lei et al. 2009, ZHENG Shi-xing et al. 2011) and numerical wind tunnel simulation (Su Yang et al. 2015, Lining Liu et al. 2017). During the vehicle aerodynamic characteristics study, the study models are divided into two kinds, including static vehicle-bridge model (HAN Yan et al. 2014, GUO Wen-hua et al. 2015) and dynamic vehicle-bridge model (CUI Tao et al. 2013). In the process of fluid domain numerical analysis vehicle is stationary on the bridge for the static vehicle-bridge model, and the vibration of vehicle-bridge system is ignored. But for the dynamic vehicle-bridge model, in the process of fluid domain numerical analysis the vehicle moving on the bridge and the vibration of vehicle-bridge system is considered at the same time. Nowadays research on the aerodynamic characteristics of vehicle, the static vehicle-bridge system is the main method used, then based on the vehicle aerodynamic coefficients study the vibration characteristics for vehicle running on the bridge (HAN Yan et al. 2015). At present, there are less research results in the

Paper Received Novenber, 2017. Revised December, 2018. Accepted December, 2018. Author for Correspondence: Ji-guo Zhou

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vehicle aerodynamic characteristics based on dynamic vehicle-bridge model. In the process of studying the aerodynamic characteristics of vehicle, the established research model mostly not be able to consider both the moving of vehicle on the bridge and the vibration of vehicle-bridge system.

In this paper, a three-dimensional numerical wind tunnel model of vehicle static on the bridge is established based on CFD (Computational Fluid Dynamics) numerical simulation. Meanwhile, a three-dimensional numerical wind tunnel model which will consider both the moving of vehicle on the bridge and the vibration of vehicle-bridge system is established based on the FSI (Fluid-solid interaction) numerical simulation. Then based on the two different models, study the differences of aerodynamic coefficients of vehicle and the differences of critical driving safety wind speeds.

NUMERICAL SIMULATION OF STATIC VEHICLE-BRIDGE MODEL

Based on software FLUENT establish numerical tunnel model of vehicle stationary on bridge to study the vehicle aerodynamic characteristics and analyze the flow field domain for wind-vehicle-bridge coupling system. A three-dimensional numerical wind tunnel model of vehicle static on the bridge is established based on CFD numerical simulation. For the numerical tunnel model, the windward boundary condition is velocity inlet, the leeward boundary condition is pressure outlet, both rest sides conditions are symmetry. For fluid computation, determine the size of the numerical model with the considering of clogging effect to make the windward modeling area and numerical wind tunnel cross section area ratio lower than 5%. A local mesh encryption method is presented on the fluid mesh to make the wall y^+ function value ($y^+ = y\sqrt{\tau_w / \rho} / \nu$) between 30~300 at the vehicle and bridge boundaries. Where y is the distance from the unit center to the wall, μ is aerodynamic viscosity, ρ is air density, τ_w is wall shear stress. The pulsating flow field is simulated by the turbulence intensity 5% and Turbulent viscosity ratio 5.

Picked up the bus as investigation subject. The vehicle body presented in Fig.1 is10.49m long, 2.5m wide and 3.6m high. The forms of bridge cross section and the position of the vehicle on the bridge are shown in Fig.2. The vehicle is on the windward side of the bridge section and the flow source comes from the left side of the bridge cross section. The tetrahedral prism is taken for meshing numerical analysis model of fluid flow and use varied grade of cell to make the mesh could control the changes of elements size around the vehicle and bridge areas. The model section of numerical wind tunnel and the meshing at vehicle location are shown in Fig.3~4.

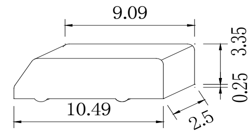


Fig.1 Vehicle model（unit: m）

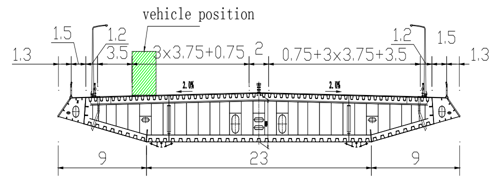


Fig.2 Bridge cross section（unit: m）

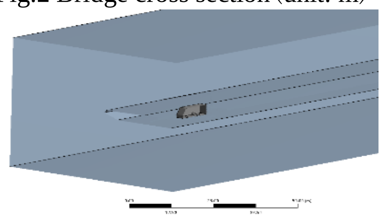


Fig.3 Numerical tunnel model cross section

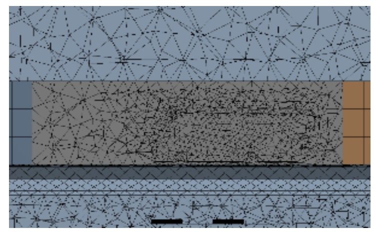


Fig.4 Numerical tunnel mesh model cross

NUMERICAL SIMULATION OF DYNAMIC VEHICLE-BRIDGE MODEL

According to wind pressure characteristics of vehicle and bridge subject, the coupling vibration of the vehicle-bridge system and the data transmission characteristics of the coupling system, this paper proposes two-way fluid-solid coupling method to study the wind-vehicle-bridge coupling system. So, a three-dimensional numerical wind tunnel model which will consider both the moving of vehicle on the bridge and the vibration of vehicle-bridge system is establish

For the wind-vehicle and wind-bridge fluid domain, vehicle-bridge system solid domain, the main assumptions in the process of coupling vibration numerical simulation analysis of wind-vehicle-bridge system are as follows. (1) Ignore the influence of bridge detail components in fluid domain, such as the inclined cables and bridge railings. (2) Mainly research the vibration characteristics of wind-vehicle-bridge system while the vehicle running away from the bridge tower location. (3) Vehicle wheels always keep in contact with the deck and vehicles drive at a steady speed on the bridge. (4) The attachments of vehicle-bridge system will be simplified to linear springs and viscous dampers.

By defining vehicle and bridge interface in coupling interface, the interaction between fluid domain and solid domain is transmitted. The fluid domain and solid domain are calculated respectively in each load step. The two-way fluid-solid coupling numerical simulation process of wind-vehicle-bridge system is shown in the Fig.5.

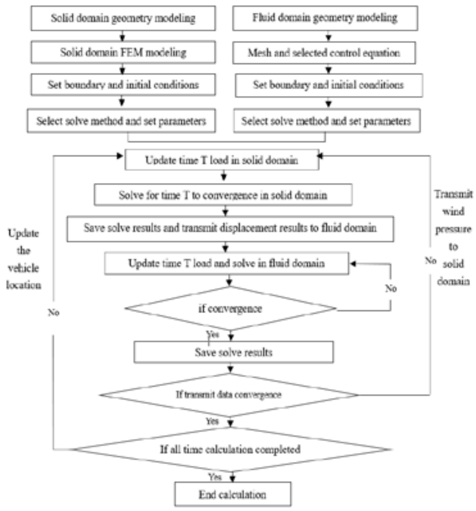


Fig.5 Fluid-solid interaction analysis process

At each load step, firstly study the effect of wind action on vehicle and bridge in the fluid domain. Then, transferring the wind pressure acting on the vehicle and bridge which are got from the fluid domain analysis to the solid domain as the loads acting on the vehicle and bridge for computing the coupling vibration of vehicle-bridge system. Last, transfers the displacement of vehicle and bridge which got from solid domain analysis to the fluid domain as the wall motion of vehicle and bridge for numerical analysis in the fluid domain. At each load step, transfer data between fluid domain and solid domain and analyze separately a few times until the transferring data stability or achieving specified times. Then the next load step starts to analyze.

For the dynamic vehicle-bridge model, the fluid numerical analysis model is similar to the static vehicle-bridge model. The solid numerical analysis method and parameters adopt the following settings. Simplifies vehicle as the combination of rigid bodies which connected by several springs and damping devices. The masses of the vehicle model all concentrate on the rigid bodies. In the vehicle model, it is assumed that the tires contact the bridge deck without separation. The suspension system and energy dissipation of the vehicle model are modeled separately with springs and viscous damping(Fig.6).

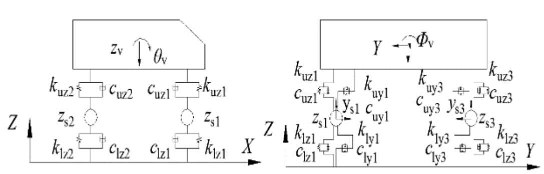


Fig.6 Numerical model of vehicle

Where Fig.6 shows the simplified vehicle analysis model. The displacements of the rigid body of the vehicle express as: vertical displacement Z_V, lateral displacement Y, pitching displacement θ_v, rolling displacement ϕ_v.

Based on a generalized long-span cable-stayed bridge, this paper analyzes the vibration characteristics of wind-vehicle-bridge system. The sketch of the bridge and vehicle location is illustrated in Fig.2. The bridge which belongs to half floating structural system has a main span of 620m and two side spans of 295m each. Introducing equivalent elastic modulus to sufficiently consider the effects of sag. Stress stiffening applies to sufficiently consider the influence of axial force on bending stiffness. Bridge deck and stay cable were established to study the coupling vibration of vehicle-bridge system based on the software ANSYS and ignore the effect of deck roughness in the coupling system. During mesh division of the bridge, tetrahedral solid 187 elements and hexahedral solid 186 elements which support plasticity, super-elasticity, stress stiffening, large deflection and large strains were applied in the solid model structure. Link180 elements were employed in the line body. Combine 14 element were applied to the vehicle springs and vehicle damping. Contact 174 element and target 170 element were utilized in the wheel contact with the bridge deck. Finally, the bridge grid and model could be obtained, as showed in Fig.7.

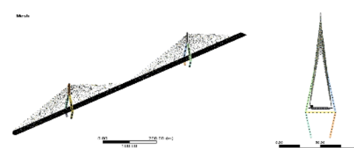


Fig.7 Numerical model of vehicle – bridge

AERODYNAMIC AND VIBRATION CHARACTERISTICS ANALYSIS

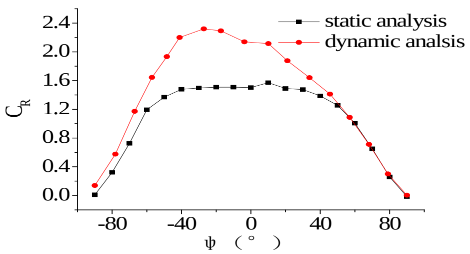
Aerodynamic characteristics of vehicle

The vehicle body bears a joint action of wind load which consisted of front wind action caused by vehicle running and natural wind action. The aerodynamic forces and moments on the vehicles have six components, which are the drag force, side force, lift force, rolling moment, pitching moment and yawing moment. The non-dimensional aerodynamic side force coefficients C_S, lift force coefficient C_L and moment coefficients C_R are defined as:

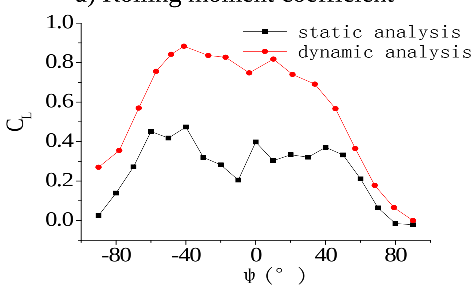
$$C_S=F_S/(0.5\rho V^2HL) \tag{1}$$
$$C_L=F_L/(0.5\rho V^2HL) \tag{2}$$
$$C_R=M_R/(0.5\rho V^2B^2L) \tag{3}$$

Where ρ is the air density(1.225kg/m3), L is the length of the vehicle, B is the width of the vehicle, H is the height of the vehicle. F_S is the side force, F_L is the lift force, M is the rolling moment, V is the resultant of a natural wind vector and the wind induced by vehicle running.

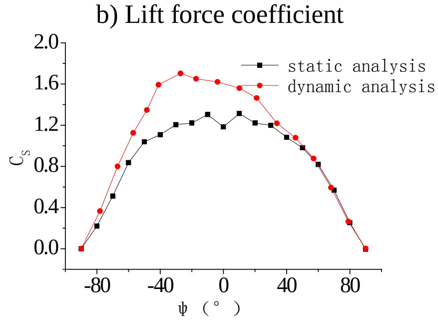
In this section, based on static vehicle-bridge model and dynamic vehicle-bridge model, study the vehicle aerodynamic characteristics respectively for the wind-vehicle-bridge system by comparative analysis the aerodynamic force coefficients of the two different analysis models. The wind yaw angle is 0 degree when the vehicle under the lateral wind action. The wind yaw angle is positive when the vehicle under the front wind action. The change rule of the aerodynamic force coefficients along with wind yaw angles within ±90 degrees is shown in Fig.8. Where static analysis is based on the static vehicle-bridge model which ignores the interaction between natural wind and vibrations of vehicle-bridge system. Where dynamic analysis is based on the dynamic vehicle-bridge model which considers the interaction between natural wind and vibrations of vehicle-bridge system.



a) Rolling moment coefficient



b) Lift force coefficient



c) Side force coefficient

Fig.8 Aerodynamic force coefficients of vehicle vs. yaw angles

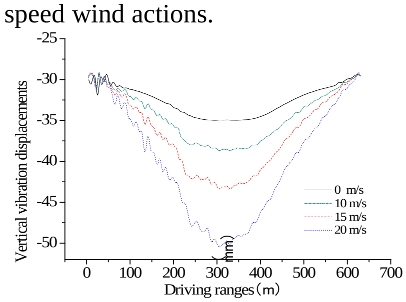
Compare the results of the two different analysis methods, it can conclude that the analysis results exist certain differences within ±90 degrees. The causes for the different conclusions are that vehicle and bridge subject the different wind yaw angle for the different analysis model. The vehicle and bridge are under the same wind yaw angle at the same time for the static vehicle-bridge model. But the vehicle and bridge are under the different wind yaw angle at the same time for dynamic vehicle-bridge model, because the vehicle subject the joint wind action which consists front wind action caused by vehicle running and natural wind action but the bridge subject the natural wind action only.

The rolling moment coefficients, side force coefficients and lift force coefficients of the vehicle obtained through dynamic analysis model are slightly larger than that obtained through static analysis model. There is an obvious difference between -40 to 40 degrees and the biggest difference for vehicle aerodynamic coefficients obtained from the different analysis method reaches 30%.

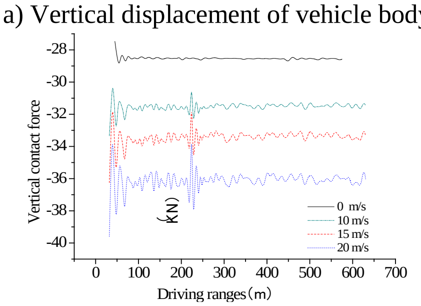
For both analysis model, the rolling moment and side force coefficient values are relatively large around 0 degree. It is easy to see that, the larger wind pressure on vehicle leads the larger rolling moment coefficient and side force coefficients when vehicle subjected the lateral wind excitation. Through this research, this paper concludes that the uneven distribution of wind pressure on the vehicle surface will also leads the larger rolling moment coefficients and side force coefficients when vehicle subjected wind excitation around 0 degrees.

Vibration characteristics of vehicle

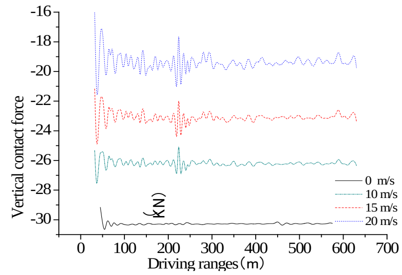
Vehicle running on smooth deck bridge at 90 km/h speed under the 0m/s, 10m/s, 15m/s, 20m/s speed wind excitation respectively, the change rule of vertical vibration of car body and the contact force between vehicle wheels and bridge deck which obtained based on dynamic vehicle-bridge model are shown in the Fig.9. It can be observed form the different vehicle vibration value for the different speed wind action, vertical displacement of car body fluctuates and increase synchronously with the wind speed increase in the driving process. The change rules of car body displacement are basically identical for different speed wind actions.



a) Vertical displacement of vehicle body



b) Windward wheel contact force



c) Leeward wheel contact force

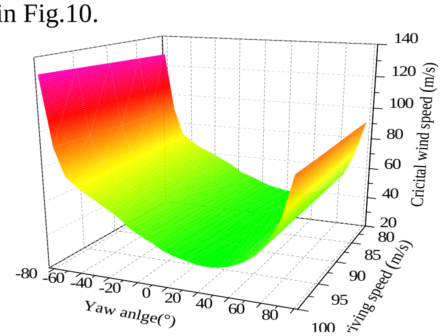
Fig.9 Vertical vibration of car body and wheel contact force vs. driving distance

It is easy to see from the contact force, the large fluctuation of the wheel contact occurs at the initial running, but it tends to be stable with the vehicle running. Because of the rolling degree of freedom, the rolling angle generates under the cross-wind action which leads the leeward wheel contact force larger than the windward wheel contact. The phenomenon that the windward wheel contact force decreases and leeward wheel contact force increase along with wind speed increase verified the dynamic model and the analysis method. From the variation of wheel contact force, it can be observed that the vibration characteristics of the vehicle mainly decided by the vehicle-bridge system and the vibration displacement are influenced by natural wind load when vehicle running on a bridge under different speed wind action.

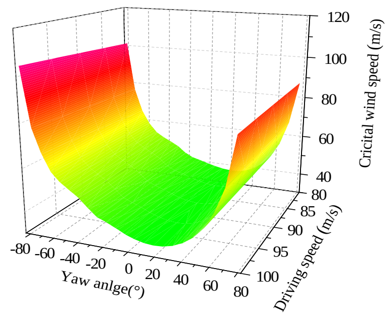
DRIVING SAFETY ANALYSIS

Overturning critical wind speeds

In this section, study the overturning critical wind speed based on the former aerodynamic coefficients and wheel contact force of the different numerical simulation model. Assume the variation of wheel contact force accord with normal distribution when the vehicle running on bridge, and taking 95% reliability of wheel contact force with no existence of suspending plate as the evaluation criteria of driving safety (Li Yongle et al. 2012). Studying the driving safety based on the static vehicle-bridge model and dynamic vehicle-bridge model, the change rules of overturning critical wind speeds along with the driving speed and wind yaw angle are shown in Fig.10.



a) Static vehicle-bridge system



b) Dynamic vehicle-bridge system

Fig.10 Overturning critical wind speed

By calculation the two numerical simulation models, it can be got that minimum critical wind speed does not occur on the wind yaw angle of 0 degree but on the wind yaw angle around 20~30 degrees. This predicts that the critical wind speed is not the minimum when the vehicle running on a bridge under cross-wind action with contrast vehicles being more prone to overturn when running on the bridge under wind action of 20~30 degrees.

Based on the static analysis model and the dynamic analysis mode, the overturning lateral critical wind speed and the overturning minimum critical wind speed are shown in Table1

Table1 Overturning critical wind speeds (m/s)

Critical wind speed	Static analysis 80	90	100	Dynamic analysis 80	90	100
Lateral wind speed	42.99	41.67	40.55	39.09	38.32	37.63
Minimum wind speed	38.27	37.04	35.68	37.05	36.13	35.07

In Table 1, where lateral wind speed represents the critical wind speed when the vehicle running on bridge under cross wind action, minimum wind speed represents the critical wind speed when the vehicle running on the bridge under the wind action on yaw angles ranges of -90 to 90 degrees.

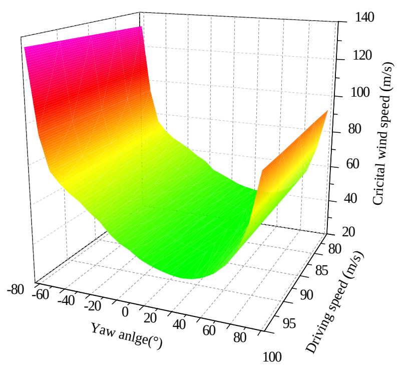
Based on the two different analysis models both overturning critical wind speed decrease with the driving speed increase while vehicle running on a bridge at 80-100 km/h speed. Lateral critical wind speed and minimum critical wind speed analyzed from dynamic analysis model shows a slightly smaller than that analyzed by static analysis method. The biggest difference of critical wind speed between static vehicle-bridge model and dynamic vehicle-bridge model approach 10%.

By the contrast between the critical wind speeds, the overturning critical wind speed which is calculated while vehicle running on bridge under the cross-wind action is not the minimum critical wind speed which is calculated while vehicle running on bridge under natural wind action with the range of -90 to 90 degrees yaw angles. The biggest difference of critical wind speed between lateral wind speed and minimum wind speed approach 12.3%. This predicts that taking safety critical wind speeds under cross wind excitations as safety critical wind speeds are relatively less safe for vehicle running on a bridge under different yaw angles wind excitations.

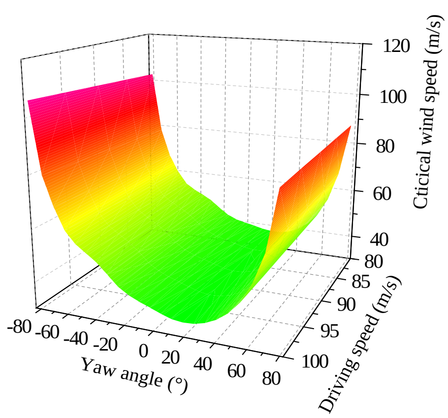
Sideslip critical wind speeds

This section studies the sideslip critical wind speed while the vehicle running on a bridge under wind action by adopting the consistent parameters used in calculating the overturning critical wind speed. When deck conditions are dry, wet, snow and ice road the adhesion coefficients μ_s are 0.7、0.5、0.15、0.07 respectively.

Studying the driving safety based on the static vehicle-bridge model and dynamic vehicle-bridge model, the change rules of sideslip critical wind speed along with the driving speed and wind yaw angle are illustrated in Fig.11.

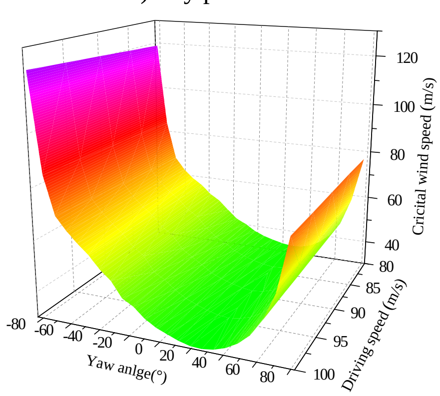


(a) Static vehicle-bridge model

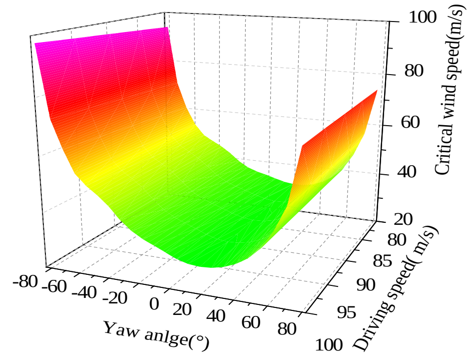


(b) Dynamic vehicle-bridge model

a) Dry pavement

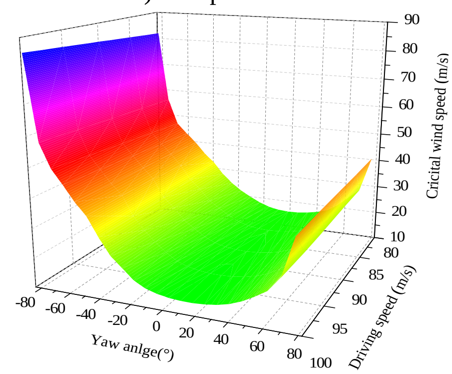


(a) Static vehicle-bridge model

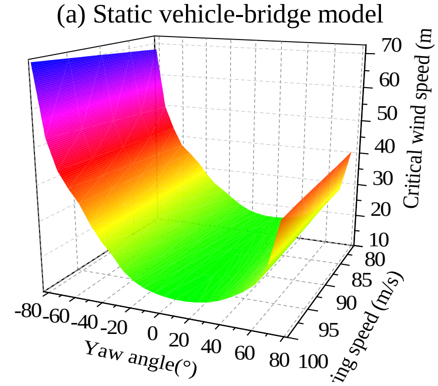


(b) Dynamic vehicle-bridge model

b) Wet pavement

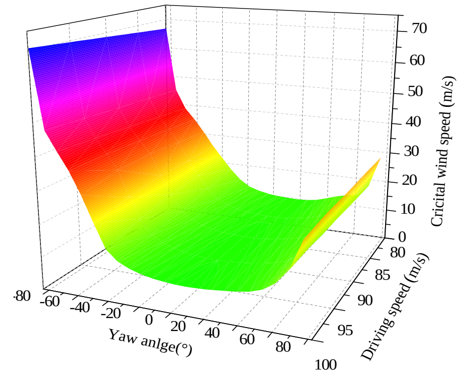


(a) Static vehicle-bridge model

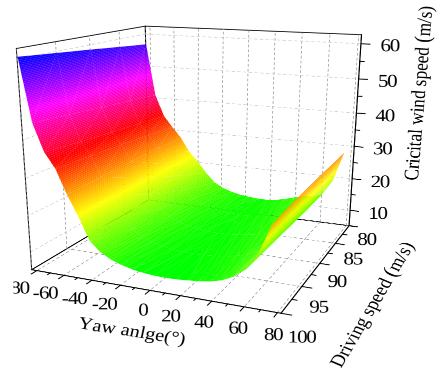


(b) Dynamic vehicle-bridge model

c) Snow pavement



(a) Static vehicle-bridge model



(b) Dynamic vehicle-bridge model

d) Ice pavement

Fig.11 Sideslip critical wind speeds under different road conditions

It can be predicted from the value of sideslip critical wind speeds at different pavement conditions, the minimum critical wind speed does not occur on the wind yaw angle of 0 degree, but on the wind yaw angle around 10~20 degrees. This predicts that the critical wind speed is not the minimum when a vehicle running on a bridge under cross wind action. By contrast, vehicle is more prone to sideslip when running on the bridge with dry, wet, snowy and ice pavement under the wind action around 10~20 degrees.

Based on the static analysis model and dynamic analysis model, the sideslip critical wind speeds and minimum critical wind speeds for a vehicle running on a bridge with different road conditions under wind action are given in Table 2~3.

Table.2 Sideslip critical wind speeds based on static vehicle-bridge model (m/s)

Pavement conditions	Critical wind speed	Static analysis		
		80	90	100
Dry	Lateral	44.37	43.08	42.09
	minimum	39.84	38.57	37.22
wet	Lateral	37.04	36.05	34.78
	minimum	33.14	31.78	30.61
Snow	Lateral	17.50	16.03	14.95
	minimum	15.91	14.98	14.24
ice	Lateral	10.37	9.67	8.89
	minimum	9.90	9.28	8.88

Table.3 Sideslip critical wind speeds based on dynamic vehicle-bridge model (m/s)

Pavement conditions	Critical wind speed	Dynamic analysis		
		80	90	100
dry	lateral	39.43	38.84	38.11
	minimum	37.30	36.230	35.26
Wet	lateral	33.99	33.23	32.20
	minimum	31.56	30.54	29.67
snow	lateral	16.98	15.97	15.10
	minimum	15.95	15.30	14.47
ice	lateral	10.56	10.02	9.54
	minimum	10.19	9.59	9.03

It can be concluded from the comparison of critical wind speed obtained from static vehicle-bridge model and dynamic vehicle-bridge model, sideslip critical wind speed obtained from two different analysis models decreases along with driving speed increase when vehicle running on bridge at 80-100km/h speed. Sideslip critical wind speeds obtained from the static vehicle-bridge model are slightly larger than the dynamic vehicle-bridge model when the vehicle running on dry and wet pavement, the maximum difference of which is 12.5% for lateral critical wind speed and 6.8% for minimum critical wind speed. Sideslip critical wind speeds obtained from the static vehicle-bridge model are slightly smaller than the dynamic vehicle-bridge model when the vehicle running on snow and ice pavement, the maximum difference of which is 7.3% for lateral critical wind speed and 6% for minimum critical wind speed. This anticipates that there is a larger difference between the two analysis models for sideslip critical wind speeds. So, study driving safety should adopt the dynamic analysis model which considers both the moving of vehicle on the bridge and the vibration of vehicle-bridge system.

It can be concluded from the comparison between lateral critical wind speed and minimum critical wind speed, the sideslip minimum critical wind speed usually lesser than the lateral critical wind speed. The biggest difference of critical wind speed between lateral wind speed and minimum wind speed approach 8.8%. This also predicts taking safety critical wind speeds under cross wind excitations as safety critical wind speeds are relatively less safe for vehicle running on a bridge under different yaw angles wind excitations.

From the comparison between overturning critical wind speeds and sideslip critical wind speeds it can be got that the overturning critical wind speeds are slightly smaller than sideslip critical wind speeds when vehicle running on the bridge of dry pavement, but overturning critical wind speed is slightly larger than sideslip critical wind speed when vehicle running on the bridge of wet, snow and ice pavement. So, this predicts the vehicle is most likely to overturn when vehicle running on a bridge with a dry road and more likely sideslip when vehicle running on a bridge with wet, snow and ice road.

CONCLUSIONS

Based on the CDF numerical simulation and fluid-solid numerical simulation, the static vehicle-bridge model and dynamic vehicle-bridge model are established separately in this paper. Through comparative study comes to the following conclusions.

(1) It should consider the interaction between the

vehicle-bridge system and natural wind environment to study the aerodynamic characteristics and driving safety when vehicle running on a long-span cable-stayed bridge under wind action.

(2) Taking safety critical wind speeds under cross wind excitations as safety critical wind speeds are relatively less safe for the vehicle running on a bridge under different yaw angles wind excitations.

(3) The vehicle running on a bridge at 80~100km/h speed under wind action is more prone to sideslip when the bridge deck is dry, wet or snow road but more prone to sideslip when the bridge deck is ice road.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support provided by the central university basic scientific research funds grant no. CHD2011JC195, by the Jilin province department of education science and technology research projects (JJKH20180305KJ) and (JJKH20190622KJ). This work is partially supported by the Chang'an University.

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基於靜止與動力模型的車輛氣動特性差異研究

周記國
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摘要

風-車-橋系統的耦合振動對車輛的行車舒適和行車安全產生較大影響。建立靜止和動力分析模型，對車輛氣動特性隨風偏角的變化規律進行研究。基於靜止與動力車-橋數值風洞模型，分析車輛分別在幹、濕、雪、冰路面狀況下以不同速度行駛，在不同偏角風荷載作用下車輛發生傾覆和側滑時的安全臨界風速。結果表明：研究車輛的氣動特性及行車安全應當考慮車-橋系統與自然風環境間的相互作用，車輛在大跨度橋樑上行駛，取側向風荷載作用研究車輛的行車安全不是最不利狀況。