J. Wind Eng. Ind. Aerodyn. 159 (2016) 65–79

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Numerical analysis on the difference of drag force coefficients of bridge deck sections between the global force and pressure distribution methods

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ARTICLE INFO

Keywords:
Bridge deck
Drag force coefficient
Pressure drag force
Friction drag force
Numerical simulation

ABSTRACT

To analyze the difference of drag force coefficients of bridge sections obtained by the global force and pressure distribution methods, three-dimensional numerical simulations on the drag force coefficients of three typical sections are carried out. Firstly, after the numerical simulation method is validated, the percentage contribution of the friction drag force coefficient of the three sections under varying wind attack angles are investigated. Furthermore, the effect of the Reynolds number and handrails on the percentage contribution of the friction drag force coefficient is analyzed, and the results show that while the Reynolds number has an insignificant effect, the handrails' effect is significant. Due to the importance of the contribution of the friction drag force for streamlined sections, more cases are simulated to investigate the percentage contribution of the friction drag force coefficient by varying the aspect ratio and fairing angle using the Sutong Bridge's cross section as an example. The correction coefficients of the drag force coefficients obtained by the pressure distribution method for streamlined sections are obtained by the least square principle. The research conclusions can provide a reference for the differences of the drag force coefficient measured by the global force and pressure distribution methods for engineering practice.

1. Introduction

With the rapid development of transportation infrastructures in China, more and more long-span bridges crossing mountains, rivers, and lakes are under construction and are being proposed. These long-span bridges with low natural frequencies are very sensitive to wind actions. In the wind resistance analysis, static coefficients are the key parameters for analyzing the aerostatic instability, buffeting response, and galloping stability of bridges. Thus, accurate evaluations of the static coefficients are very essential for the wind-resistant design of long-span bridges.

Currently static coefficients of bridge deck sections are mainly measured by the global force and pressure distribution methods in wind tunnel experiments. For the global force method, force balance is used to measure the static wind loads. Therefore, it is impossible for this method to know the local pressure of the cross section, which is unfavorable for the detailed analysis of aerodynamic force and the optimum design of the cross section. In comparison, the pressure distribution method can obtain the pressure of each local region by placing pressure taps on the cross section, and then the static wind loads of the cross section can be obtained by integrating the wind pressures. However, this method can only obtain the pressures normal to the cross section and typically cannot measure the shear stresses that generate the friction drag forces of the cross section. Also, the pressures on the ancillary facilities of the bridge deck section cannot be obtained by this method. Thus, although the pressure distribution method can measure the pressure details on the cross section, it is likely to cause some errors on the identification of the static force coefficients. The previous studies on streamlined bridge section using global force and pressure distribution methods found that both methods were in good agreement for the lift force coefficient and the pitching moment coefficient. However, the drag force coefficient measured by the pressure distribution method was only about two-thirds of that measured by the global force method (Ricciardelli and Hangan, 2001; Han et al., 2013). Liu and Chen (2007) measured the aerostatic coefficients of a rectangular cross section by using the two methods in wind tunnel tests. The results showed that, for the bluff rectangular cross section, the drag force due to friction had small impact on the aerostatic coefficients with varying wind attack angles. The sectional model tests of a streamlined cross section by Li (2003) showed that the contribution of the friction drag force decreased with the increasing Reynolds numbers in a certain range of the Reynolds number. He

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http://dx.doi.org/10.1016/j.jweia.2016.10.004
Received 2 December 2015; Received in revised form 10 October 2016; Accepted 10 October 2016

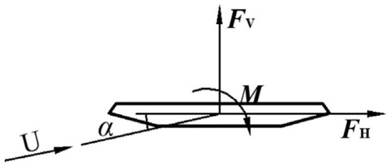

Fig. 1. Sign convention for aerodynamic forces and wind attack angle.

revealed the difference of the streamlined section's aerostatic coefficients measured by the two methods with different Reynolds numbers. However, in these studies, the discrepancies between these two methods were not deeply investigated because the aim of their papers was not to compare these two methods. In addition, there are difficulties in analyzing the differences deeply with the wind tunnel tests because the shear stress in each local region and the pressure on the ancillary facilities of the bridge deck section all cannot be measured directly.

Numerical simulation methods have the advantages of repeatability, less manpower demanding, and the visibility of the flow field compared with the wind tunnel test. With the rapid development of computer technology and the computational fluid dynamics (CFD) theory, CFD technology has been widely used as an analysis method for wind engineering, sometimes in lieu of wind tunnel experiments. The aerodynamic parameters, for the rectangular section or the streamlined section, were investigated based on the CFD technology by many researchers (Shimada and Ishihara, 2002, 2012; Sun et al., 2009; Mannini et al., 2011; Tamura and Ono, 2003; Sohankar, 2008; Sarwar et al., 2008; Huang et al., 2009; Qu and Liu, 2007; Cao et al., 2000; Bruno et al., 2010, 2012; Mannini et al., 2010, 2011). In addition, the pressures normal to the cross section and the shear stresses on the entire cross section including the ancillary facilities can be more conveniently obtained in CFD simulations, and correspondingly the friction drag force can be calculated. Ricciardelli and Hangan (2001) investigated the discrepancies in the experimental mean aerodynamic coefficients between the force and pressure measurement systems and defined the discretization error and shear-stress error using CFD method, in which a 2D RANS approach was adopted. In their study, different turbulence models were tested, and the contribution of the shear stress in the global force versus the wind attack angle was analyzed. However, the parametric analysis of the discrepancies in the aerodynamic coefficients between the global force and pressure distribution methods was not conducted.

In some situations such as in the field monitoring system, it is necessary to use the pressure distribution method to measure the stationary aerodynamic forces of the bridge deck section. In view of this, it is significant to carry out the parametric analysis of the discrepancies in the two methods and correct or compensate the results measured in field when necessary. In addition, the discrepancies in the lift force and the pitching moment coefficients are relatively small as shown in the previous analysis. Therefore, this paper investigates the influence factors on the difference of drag force coefficients between the global force and pressure distribution methods using CFD simulations. Meanwhile, the present study develops a methodology to correct the coefficient for the drag force coefficient when it is measured by the pressure distribution method.

Simulations of the drag forces of typical cross sections are carried out in Section 2, which illustrates the definition of the drag force and simulation methods including the fluid domain and boundary conditions. In Section 3, the variations of the drag force coefficients of typical sections with the varying wind attack angle are investigated, and the mean pressure and shear stress distributions on the sections are studied. Furthermore, the effect of the Reynolds number and handrails on the friction drag force coefficients are analyzed. In Section 4, more parameters including the aspect ratio and fairing angle are analyzed, and the correction coefficients of the drag force coefficients by the pressure distribution method are obtained by the least square principle based on the numerical results. Finally, some conclusions are drawn in Section 5.

2. CFD analysis of the drag forces of typical cross sections

2.1. Definition of the drag force

F_H, $F_{V,}$ and M are the drag force, lift force, and pitching moment per unit span length of the bridge deck in the body-axis coordinate system, respectively, and α is the wind attack angle as shown in Fig. 1. In the numerical simulation, the global force, the local pressures, and the shear stresses all can be easily obtained. For the analysis of the difference of the drag force coefficients between the global force and pressure distribution methods conveniently, the global drag force, $F_{H,}$ is defined as the sum of the pressure drag force and the friction drag force as:

$$F_H=0.5\rho U^2 C_H(\alpha)HL=F_{HP}+F_{SS} \tag{1}$$

where ρ is the air density; U is the oncoming wind velocity; H is the height of the bridge deck; L is the span-wise length of the bridge deck; $C_H(\alpha)$ is the global drag force coefficient; F_{HP} and F_{SS} are the pressure drag force and the friction drag force that can be computed by integrating the pressures and the shear stresses in the simulation and expressed as:

$$F_{HP}=\sum_{i=1}^{n}\overline{p}_i\cdot\Delta L_i\cdot\sin(\theta_i) \tag{2}$$

$$F_{SS}=\sum_{i=1}^{n}\overline{\tau}_{ix}\cdot\Delta L_i \tag{3}$$

where $\overline{p}_i$ is the mean pressure at the monitoring point i; ΔL_i is the tributary length of the monitoring point i; θ_i is the angle between the pressure direction and vertical axial in the body-axis coordinate; $\overline{\tau}_{ix}$ is the shear stress parallel to the direction of the drag force at the monitoring point i; and n is the total numbers of the monitoring points based on the grid mesh of the section.

In addition, F_{HP} can be defined as:

$$F_{HP}=0.5\rho U^2 C_{HP}(\alpha)HL \tag{4}$$

where $C_{HP}(\alpha)$ is the pressure drag force coefficient.

Therefore, the global drag force and pressure drag coefficients can be expressed as:

$$C_H(\alpha)=F_H/0.5\rho U^2 HL \tag{5}$$

$$C_{HP}(\alpha)=F_{HP}/0.5\rho U^2 HL \tag{6}$$

2.2. Simulation method

The 3D steady-state RANS simulations, which are considered a good compromise between the achievable quality of the results and the computational effort for the analyzed problem have been performed to compute the mean pressure, shear stress distributions, and the static forces. The numerical solutions are carried out using ANSYS CFX 14.5.