Journal of Wind Engineering & Industrial Aerodynamics 172 (2018) 298–316

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

A numerical investigation of Reynolds number sensitivity of flow characteristics around a twin-box girder

Shujin Laima [a,b,c], Chao Jiang [c], Hui Li [a,b,c,*], Wenli Chen [a,b,c], Jinping Ou [a,b,c]

[a] Key Lab of Smart Prevention and Mitigation for Civil Engineering Disasters of the Ministry of Industry and Information, Harbin Institute of Technology, Harbin, 150090, China
[b] Key Lab of Structures Dynamic Behaviour and Control of the Ministry of Education, Harbin Institute of Technology, Harbin, 150090, China
[c] School of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China

ARTICLE INFO

Keywords:
LES
Reynolds number effects
Flow characteristics
Twin box girder
Turbulence transition

ABSTRACT

A numerical investigation of Reynolds number sensitivity on flow past a twin-box girder was performed using large eddy simulation (LES) with Reynolds numbers of $1e2 \le Re \le 1e7$. The simulation results reveal that the flow characteristics around the twin-box girder show different Reynolds number sensitivity according to the flow region and the flow state. At the leading edge, the flow experiences laminar separation-laminar reattachment state ($1.5e3 < Re < 6e3$), laminar separation-turbulence reattachment state ($6e3 \le Re \le 8e4$), and turbulence separation-turbulence reattachment flow state ($Re > 8e4$). Around the gap, four models exist depending on Reynolds number: laminar closed cavity flow ($Re < 1.6e3$), laminar open cavity flow ($1.6e3 \le Re < 5e3$), wake model ($5e3 \le Re \le 9e3$), and turbulent open cavity flow ($Re > 8e3$). In the tail of the box girder, a regular Karman vortex is first generated, and then the lower shear layer transits to turbulence, resulting in the generation of separation bubbles at the lower and upper trailing edges. However, due to the upper trailing edge being blunter than lower trailing edge, the Reynolds number sensitive range of upper trailing edge (1e2-1e7) is much wider than lower trailing edge (1e2-2e4).

1. Introduction

When flows pass over a solid body, the flow patterns and corresponding flow-induced forces have a strong correlation with the Reynolds number. For instance, it is well known that the flow pattern experiences several stages when flow passes over a rigid circular cylinder at increasing Reynolds number (Roshko, 1993; Williamson, 1996). For $Re < 5$, the flow attaches on the surface. As the Reynolds number approaches 49, a recirculation region with two symmetrical vortices forms behind the circular cylinder. In $49 < Re \le 190$, the recirculation region becomes unstable, resulting in laminar vortex shedding periodically in the wake. In the range of $Re = 190$ to 260, three-dimensional (3-D) vortex structures, i.e. mode A (vortex loops) and mode B (stream-wise vortex pairs), appear around the primary vortex. For $1e3 < Re \le 2e6$, a portion of the separated shear layer transits into turbulence and the transition point gradually moves upstream as Re increases. As Re increases up to 3.5e6, the separated shear layer first reattaches on the surface then separates much further downstream, inducing a narrower wake. When the Reynolds number is larger than 3.5e6, the transition point is in front of the separation point and generates a turbulent boundary layer separation. Accompanying the development of the flow pattern, the flow characteristics, e.g. drag force, lift force, and vortex-shedding, also change with increasing Reynolds number (Williamson, 1996; Norberg, 2003; Zdravkovich, 1997).

As a typical structure, the box girder with sharp edges is widely used in modern long-span bridges. The Reynolds number effects of box girders have attracted an increasing amount of attention in recent years. For a sharp-edge box girder, under the effect of adverse pressure gradients at the leading edges, the flows usually separate in the vicinity of windward corners. If the stream-wise aspect ratio is small, the separated shear layer does not reattach on the surface. Therefore, it seems that the flow characteristics may have less sensitivity to Reynolds number for this case. However, as is well known, the stream-wise aspect ratio of box girder for long-span bridges is usually very large ($B/H > 7$) to satisfy transport requirements. For a bluff body with a large aspect ratio, the separated shear layer will reattach on the surface along with the formation of

---

[*] Corresponding author. Key Lab of Smart Prevention and Mitigation for Civil Engineering Disasters of the Ministry of Industry and Information, Harbin Institute of Technology, Harbin, 150090, China.

E-mail address: lihui@hit.edu.cn (H. Li).

https://doi.org/10.1016/j.jweia.2017.11.016
Received 7 July 2017; Received in revised form 6 October 2017; Accepted 15 November 2017

separation bubble. The separation-reattachment process is very unsteady and the characters have a strong correlation with Reynolds number. In addition, the wake also has a significant correlation with Reynolds number similar to the wake of circular cylinder. Therefore, the Reynolds number effect is a crucial factor for the flow structures and aerodynamics characteristics of bridge decks.

Some experimental studies have been carried out on the Reynolds number effects of sharp-edge box girders. Schewe and Larsen (1998) carried out a wind tunnel test for the bridge section model of the approach bridge of the Great Belt East Bridge in the Deutsche Forschungsanstalt für Luft-und Raumfart (DLR) high-pressure wind tunnel to investigate the Reynolds number effects with a range of 1e4 < Re < 1e7 based on characteristic cross-wind dimension. It is concluded that slender bodies with sharp edge cross sections, e.g. bridge box girders, do indeed suffer from considerable Reynolds number effects due to the topology variations of wake flow. Schewe (2001) confirmed that the topological structure of wake flow of bluff bodies is dependent on Reynolds number, specifically, the wake flow from the laminar separated shear layer transits to turbulence with the increase in Reynolds number. Larose and D'Auteuil (2006) reviewed the Reynolds number sensitivity of the aerodynamics of bluff bodies with sharp edges and concluded that ignoring the Reynolds number effect of bluff bodies can lead to systematic errors. Li. et al. (2014) experimentally investigated the Reynolds number effects on the flow past a twin-box girder at Re = [5.85e3 1.12e5] based on the central height of the twin-box girder. The results also indicated that the aerodynamic characteristics had obvious Reynolds number sensitivity due to the leading separation shear layers gradually transitioning into turbulence and it was concluded that the vortex-induced vibration (VIV) of the twin-box girder with higher Reynolds number has a higher critical reduced wind velocity, larger vibration amplitude, and wider lock-in range. Although there are some studies on Reynolds number effects on sharp-edge box girders, the results at high Reynolds number are very rare, which is due to the large cost of wind tunnel tests at high Reynolds numbers. As is well known, the wind tunnel test at very high Reynolds number should be carried out in expensive high-pressure wind tunnels or cryogenic wind tunnels. Fortunately, the rapid development of supercomputer technology and computational fluid dynamics (CFD) has shed light on the investigation of flow characteristics around bluff bodies at high Reynolds number.

In recent decades, CFD has become an important tool in studying flow past a bridge deck. Kuroda (1997) numerically simulated the flow around the box girder of the Great Belt East Bridge at Re = 5.0e4 (the Reynolds number is characterized by the height of box girder) with two-dimensional (2-D) laminar form. The simulated results showed that the computed drag and pitching moment agreed well with the wind tunnel test results. Computed lift coefficients were also in good agreement with the experimental results in the range of positive attack angles. However, the computed lift coefficients were somewhat different from the experimental data in the range of negative attack angles due to the simulation omitting the side rails and crash barriers, which existed in experimental model. Larsen and Walter (1997) simulated the flow past cross sections of bridge decks of the Great Belt East Bridge and 1st Tacoma Narrows Bridge and the corresponding flow-induced motions using a 2-D discrete vortex method with Re = 1.4e4 based on the height of cross section. The results showed that the wind loads, flutter wind speeds, and vertical vortex-induced responses had a satisfactory agreement with wind tunnel test results. The authors attributed the success of the simulations to the bluff nature of the cross sections and to the 2-D nature of flow around bridge girders. Bruno and Khris (2003) performed a computational study on evaluating the capability of 2-D numerical simulation for predicting the vortical structures around the deck section of the Great Belt East Bridge. In general, the ensemble-averaged models of turbulence do not properly simulate the small-scale complex eddies at the root of the vortex-formation process. Selvam (1998) carried out the 2-D and 3-D LES of flow past the deck section of Great Belt East Bridge, the results showed that only 3-D LES can capture the drag force coefficient with reasonable accuracy. Watanabe and Fumoto (2008) studied the relationship between the aerodynamic characteristics and attack angles, and the generation mechanism of the aerodynamic forces of a slotted box girder using LES with a Smagorinsky subgrid-scale stress (SGS) model at Re = 1e4 based on the height of bridge deck. The simulation results showed that the occurrence of separation-reattachment phenomenon at the lower side of leading edge of the faring makes the drag and moment increase. In addition, the authors concluded that if the section is shaped such that flow separation through the windward faring is difficult even at large attack angles, it can be said that the aerodynamic stability against static transformation is well ensured for most of the attack angles throughout the service operation of the bridge. Mannini et al. (2010) performed 2-D unsteady Reynolds-averaged Navier-Stokes simulations (URANS) of flow around inverted trapezoid cross sections with lateral cantilevers of bridge decks at Re = [1.56e3 9.3e4] based on the height of bridge deck. First, the simulations with the Spalart-Allmaras turbulence model (SA) and the linearized explicit algebraic turbulence model (LEA) were compared. The computed mean aerodynamic forces and pressures with both SA and LEA models were very close to the wind-tunnel data. However, The LEA results are more accurate than those obtained with the SA model, in particular in consideration of the bubble on the upper side of the profile near the ‘leading edge’ and on the lower side near the upstream corner. Then the effects of the sharpness of the lower corner on the aerodynamic characteristics were investigated. The numerical simulation results showed that the flow field around the bridge profile can change dramatically due to a slight rounding of the girder box lower corners. Finally, the Reynolds number effects were discussed, showing that there are significant Reynolds number effects for this type of bridge section. With the Reynolds number increased from 1.56e3 to 9.3e4, the Strouhal number increases and the mean drag decreases. The presence of rounded corners increases the sensitivity of the bridge section to Reynolds number variations.

From the above summarized results of previous publications, it seems that the both 2-D and 3-D simulations have good ability to predict the aerodynamic forces. However, it should be noted that all of the above 2-D simulations are at moderate Reynolds numbers (Re = [1e4 1e5]). In addition, being similar to the wake dynamic of flow past a circular cylinder (Williamson, 1996), the flow around the box girder experiences flow instability and transition (laminar transition to turbulence for separated shear layer and boundary layer) at increasing Reynolds number. These processes are very complex and the flow structures are three-dimensional, requiring 3-D CFD methods, such as direct numerical simulation (DNS) and LES, to be employed. For the DNS, simulation at very high Reynolds number is impossible because the very wide range that exists between the largest and smallest dissipative scales cannot be explicitly simulated even on the largest and most powerful computers (Lesieur and Metais, 1996). The alternative approach is LES. LES solves the large eddies which represent three-dimensional unsteady motions; the effects of small eddies which are smaller than the grid spacing are resolved by the SGS model. Therefore, LES is very suitable for resolving the unsteady motions around the bluff body and have much lower computational cost than DNS at high Reynolds number. For LES on flow past a bluff body, one of the most important things is choosing or creating SGS model. The Smagorinsky SGS model is most widely used, in which the eddy viscosity is assumed to be proportional to the subgrid-scale characteristic length scale and to a characteristic turbulent velocity based on the second invariant of the filtered-field deformation tensor. However, Smagorinsky's model is too dissipative close to a wall, and it does not work for transition in a boundary layer (Lesieur and Metais, 1996). In Smagorinsky's model, the main drawback is that the model coefficient should be predetermined as a constant in space and time, while the constant should be not universal in different flow fields, such as shear flows, boundary flows or transition flows. To overcome this drawback, the Dynamic Smagorinsky-Lily model was proposed (Germano et al. 1991; Lilly, 1992), in which the model coefficient is