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Aerodynamic characteristics of a streamlined box girder under non-uniform shear flow with turbulence intensity

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SUMMARY:
Non-synoptic winds such as typhoons and downbursts are usually characterized by shear flow associated with turbulence, which affects the aerodynamic performance and vortex-shedding behaviours of the long-span bridges. The previous studies concentrated on typical cylinders under uniform shear flow, while the investigation considering turbulence on real bridge girders under shear flow is quite few. This study aims to investigate the aerodynamic characteristics of streamlined box girder under non-synoptic winds characterized by velocity shear and turbulence. Multi-fan wind tunnel (MFWT) tests were used to investigate the aerodynamic performance around the streamlined box girder in non-uniform shear flow, i.e., shear flow considering different turbulence intensities. Additionally, the Large Eddy Simulation (LES) method was used to study the vortex-shedding behaviours of the streamlined box girder in shear flow. In MFWT tests, the increasing shear rate was found to be beneficial in reducing the drag and moment coefficients, but also in increasing the lift coefficient. The variation of drag coefficient along with increasing turbulence intensity is strongly nonlinear. LES results revealed that the vortex usually starts from the low-velocity side, which induced a suction effect on the low-velocity side greater than that on the high-velocity side.

Keywords: Streamlined box girder, Aerodynamic performance, Non-uniform shear flow

1. INTRODUCTION

Non-synoptic winds have significant changes in velocity and turbulence intensity (Tamura and Kareem, 2013), and they are usually responsible for huge economic and life losses (Lombardo et al, 2018). The design of long-span bridges referred on the monsoon climate is not safe enough. It is necessary to investigate the aerodynamic mechanism of typical streamlined bridge girders under non-synoptic wind environments.

To investigate the aerodynamic mechanism of oncoming shear flow on bluff bodies, some studies on typical bluff bodies in shear flow have been carried out, and disagreements in these results also were significant. (Adachi and Kato, 1975) found that both the mean drag and lift forces of a circular cylinder increased with the shear rate. However, (Kang, 2006) studied the aerodynamic characteristics of a circular cylinder in shear flow, finding that with the increase in shear rate the mean drag remains nearly constant or slightly decreases. (Cao et al, 2007) studied aerodynamic forces on a circular cylinder in linear shear flow and believed that with the increase of shear rate the lift coefficient increased and the drag coefficient decreased. The existing conclusions of typical bluff bodies in linear shear flow are conflicting and not universal, showing that there are still many issues should be solved.

Notably, all the literature reviewed above focused on the aerodynamic characteristics of bluff bodies under uniform shear flow. Turbulence generally is also attendant in non-synoptic winds. Hence, previous studies in shear flow cannot characterize the actual non-synoptic wind environment, furthermore, the streamlined box girders in long-span bridges as commonly used bluff bodies should be paid more attention. In this study, the typical streamlined box girder in long-span bridges was used to investigate the aerodynamic mechanism and vortex shedding behaviours in non-uniform shear flow considering oncoming turbulence characterized by different intensities. Multi-fan wind tunnel (MFWT) tests were used to investigate the turbulence effect on the aerodynamic forces of the streamlined box girder under different shear rates. To reveal the vortex-shedding behaviours, the Large Eddy Simulation (LES) method was validated and then used to analyse the vortex-related behaviour of the streamlined box girder in shear flow.

2. TESTING METHOD UNDER SHEAR FLOW

2.1 Experimental design

Fig. 1 shows the streamlined box girder section model used in this MFWT test. The testing model suffering from the velocity shear and turbulence was installed at the working section of TJ-5 multiple fans wind tunnel in Tongji University.

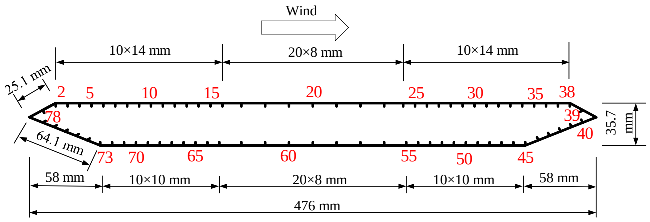


Figure 1. Arrangement of measured taps around the box girder section.

The shear rate defined with a dimensionless shear parameter (β) is expressed as:

$$\beta = G \times \frac{H}{U_C} = (\frac{dU}{dy}) \times (\frac{H}{U_C}) \tag{1}$$

where G is the velocity gradient meaning velocity increment d_v per d_y along the vertical direction; H is the height of the section, and U_C is the mean wind velocity of the oncoming flow. Fig. 2 shows the velocity gradient distribution of the oncoming shear flow.

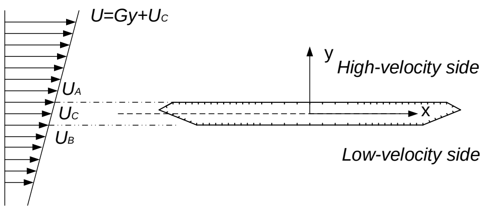


Figure 2. Schematic diagram of shear flow and bridge girder.

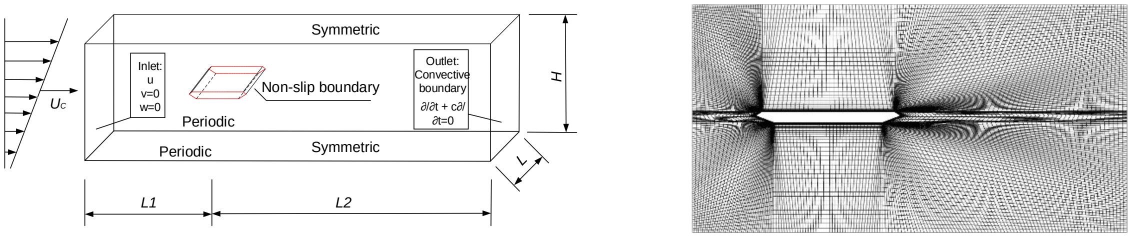
Table 1 summarizes the testing parameters, which were used to conduct the cross-over experimental design.

Table 1. Summary of wind tunnel test for shear flow

	β	I_u (%)
Level	0, 0.03, 0.05, 0.07	0, 5, 10

2.2 Numerical simulation

The shear flow was characterized by Reynolds number ($Re = 2.6 \times 10^5$) equal to the value in the MFWT test. The computational domain and the boundary conditions in LES are depicted in Fig. 3 (a), and the computational mesh is illustrated in Fig. 3 (b). To balance the simulating accuracy and time cost, it was finally determined that the number of grids in the calculation domain of this study is 1.83 million, and the time step is 0.00125s.



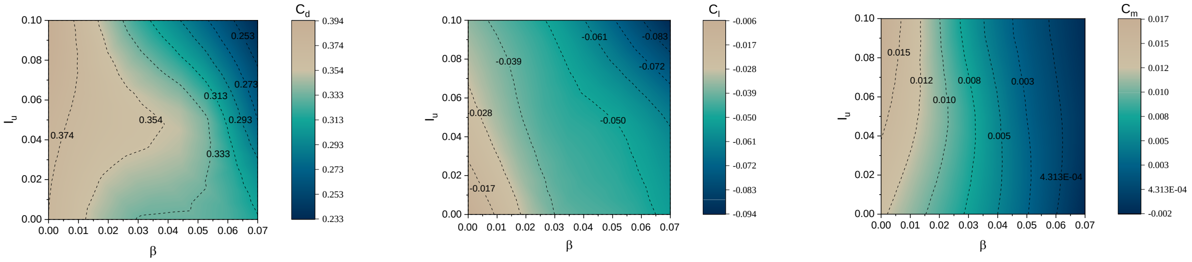
(a) Computational domain and boundary conditions (b) Grids around box girder

Figure 3. Simulation details of streamlined box girder in LES.

3. RESULTS AND DISCUSSIONS

3.1 Experimental results and discussions

Fig. 4 depicts the contour map of aerodynamic coefficients under different turbulence intensities and shear rates. As shown in Fig. 4 (a), the drag coefficient gradually decreases with the increase in shear rate. The variation of drag coefficient along with increasing turbulence intensity is strongly nonlinear. Such observations reveal strong interactions between shear rate and turbulence intensity on the drag coefficient of the streamlined box girder. As shown in Fig. 4 (b), the mean lift coefficient in shear flow is negative, which means a lift force from the high-velocity to the low-velocity side. The increase in shear rate or turbulence intensity results in the amplification of the negative lift coefficient. However, the mean moment force coefficient is almost independent of the turbulence intensity, while it only decreases with the increase in shear rate (Fig. 4(c)).



(a) Drag coefficient (b) Lift coefficient (c) Moment coefficient

Figure 4. Contour map of aerodynamic coefficient influenced by turbulence intensity and shear rate.

3.2 Numerical simulation results and discussions

Fig. 5 depicts instantaneous dynamic wake vortices around the streamlined box girder under various shear rates within the initial one period. Different from the uniform flow, the vortex structure can only be generated at the low-velocity side and then fall off to generate a series of wake vortices in the shear flow field. This indicates that the velocity shear can suppress the vortex generation on the high-velocity side of the streamlined box girder. Since the vortex always starts from the low-velocity side, the vortex at the low-velocity side has a greater suction effect than that at the opposite side, resulting in its aerodynamic lift always pointing from the high-velocity side to the low-velocity side. This is the fundamental reason that the lift coefficient measured in the wind tunnel test is negative.

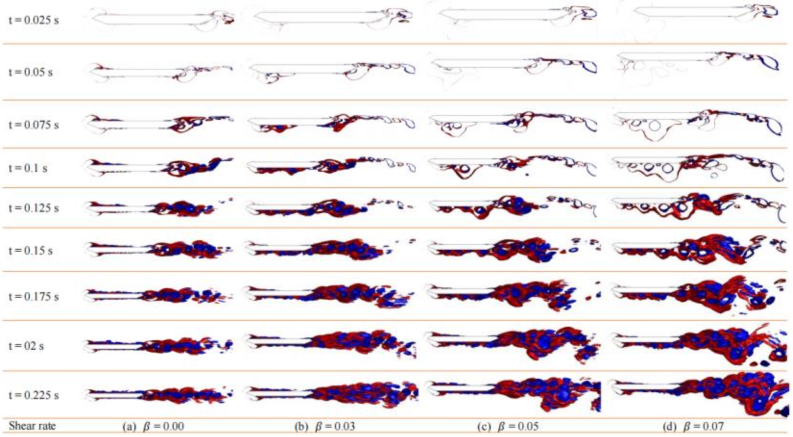


Figure 5. Instantaneous dynamic wake vortex around streamlined box girder.

4. CONCLUSIONS

In this study, MFWT tests and CFD simulations were carried out on the streamlined box cylinder in shear flow. The main conclusions are summarized as: (1) The drag coefficient and moment coefficient dwindled with the increase in shear rate, while the increase in shear rate or turbulence intensity resulted in the amplification of the lift coefficient. The variation of drag coefficient along with increasing turbulence intensity is strongly nonlinear. (2) The vortex usually starts generating from the low-velocity side, which induced a suction effect on the low-velocity side greater than that on the high-velocity side. This is the fundamental reason that the lift coefficient measured in the wind tunnel test is negative.

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