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Vortex-induced vibration of a 5:1 rectangular cylinder: A comparison of wind tunnel sectional model tests and computational simulations

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A R T I C L E I N F O

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A B S T R A C T

Considered to be representative of a generic bridge deck geometry and characterised by a highly unsteady flow field, the 5:1 rectangular cylinder has been the main case study in a number of studies including the “Benchmark on the Aerodynamics of a Rectangular 5:1 Cylinder” (BARC). There are still a number of limitations in the knowledge of (i) the mechanism of the vortex-induced vibration (VIV) and (ii) of the turbulence-induced effect for this particular geometry. Extended computational and wind tunnel studies were therefore conducted by the authors to address these issues. This paper primarily describes wind tunnel and computational studies using a sectional model in an attempt to bring more insight into Point (i). By analysing the distribution and correlation of the surface pressure around an elastically mounted 5:1 rectangular cylinders in smooth and turbulent flow, it revealed that the VIV was triggered by the motion-induced leading-edge vortex; a strongly correlated flow feature close to the trailing edge was then responsible for an increase in the structural response.

1. Introduction

The rectangular cylinder has been considered as representative of many structures in the built environment including the bridge deck. In contrast to the circular cylinder, the rectangular cylinder is characterised by permanent separation points at the leading edge causing two unstable shear layers which can interact with the after-body length or with each other in the wake, significantly affecting its response (Nakamura et al., 1991). Therefore, the aerodynamics of the flow field and related aeroelastic responses of this cylinder are highly unsteady and complicated, attracting a number of studies including the BARC study (Bruno et al., 2014).

For the rectangular cylinder with a long after-body length (if the width-to-depth ratio $B/D \geq 4$), these shear layers can be trapped underneath circulating flow which is called the separation bubble. The separation bubble can become detached and develops into the leading-edge vortex propagating downstream; its arrival at the trailing edge is phase-locked into the shedding of the trailing-edge vortex and the creation of another leading-edge vortex (Mills et al., 2003). However, this synchronisation is poor and intermittent in the case of the 5:1 rectangular cylinder, where the aforementioned shear layers reattach at points very close to the trailing edge. Wind tunnel experiments found the Strouhal number in this case is not unique; it randomly switches between two values, indicating two different flow regimes (Ozono et al., 1992).

Other literature reveals the effect of the turbulence on the separation bubble. The turbulent wind amplifies the suction peak on the surface and shifts it upstream yielding a smaller separation bubble and earlier pressure recovery (Lee, 1975). Further studies pointed out the turbulence-induced effects on the pressure distribution around a 5:1 rectangular cylinder, including a decrease in the pressure correlation and coherence (Matsumoto et al., 2003).

The elastically supported rectangular cylinder has been found to be prone to the VIV due to the motion-induced vortex shed from the leading edge or the von Kármán vortex shed from the trailing edge (Matsumoto et al., 2008). For a range of aspect ratios from 2.6 to 8, which includes the 5:1 rectangular cylinder, these mechanisms are indistinguishable. In addition, different harmonics of the VIV can be observed, which are associated with different numbers of vortices present along the surface of the body because of the long after-body length.

Further studies on the buffeting response of a bluff body have shown a significant effect of the turbulence on the pressure distribution and aeroelastic behaviour. Matsumoto et al. (1993) reported the turbulence-induced stabilisation effect on the VIV of the rectangular cylinder, due to an increase in the vorticity diffusion and thus a decrease in the strength of vortices. However, Wu and Kareem (2012), Kareem and Wu (2013) and Cao (2015) have recently pointed out the deficiencies in

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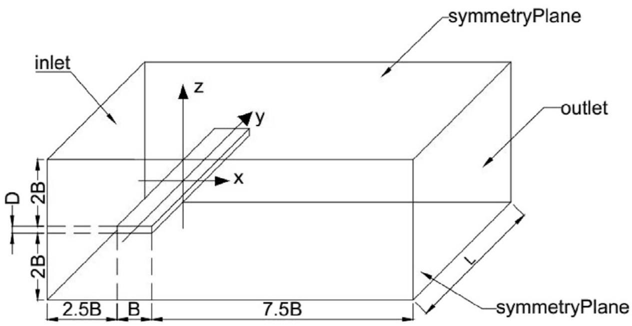

Fig. 1. Domain geometry and boundary conditions of selected patches.

the quantitative and qualitative understanding of the turbulence-induced effect on the VIV of the bluff body with a generic aerodynamic cross section and a bridge deck cross section; studies on the latter were comparatively less than those on the former. A number of collective studies on the circular cylinder reviewed by Cao (2015) showed that the turbulence produces a very strong effect on the VIV lock-in and, in some cases, the turbulence can completely suppress the VIV. Meanwhile, the wind tunnel study conducted by Goswami et al. (1993) suggested that the variation of the VIV structural response of a freely-vibrating circular cylinder in turbulent flow was minimal, compared to that measured in smooth flow. As for bridge deck cross sections including the rectangular cylinder, Kobayashi et al. (1990, 1992), Kawatani et al. (1993, 1999) conducted a series of wind tunnel tests investigating the VIV of rectangular and hexagonal cylinders having different aspect ratios in smooth and turbulent flow. The turbulence suppression effect was not observed for all cross sections. Later, Wu and Kareem (2012) and Kareem and Wu (2013) also pointed out this issue and suggested this was due to the difference in the mechanism of the VIV – whether it was motioned-induced-vortex or von-Kármán-vortex driven VIV. Given that the turbulence does not affect the motion-induced vortex, the VIV response can be increased since the turbulence weakens the von Kármán vortex and its mitigation effects on the motion-induced leading-edge vortex (Matsumoto et al., 2008; Wu and Kareem, 2012). Nevertheless, more studies are required to clarify these inconsistencies and provide a more comprehensive explanation on the mechanism of the turbulence-induced effect on the motion-induced vortex and the VIV.

Together with traditional wind tunnel tests, the development of Computational Fluid Dynamics (CFD) allows researchers to model and investigate the aerodynamics of the flow around and the aeroelasticity of the rectangular cylinder. Due to the complexity of the problem and the limitation of computational power, simulations were initially restricted to model the flow around 2D cylinders using Unsteady Reynolds-Averaged Navier-Stokes (URANS) models. Their outcomes agreed well with wind tunnel tests and offered comprehensive explanation of the vortex shedding phenomenon of the rectangular cylinder (Ohya et al., 1992; Tan et al., 1998; Larsen and Walther, 1998). Also, 2D simulations

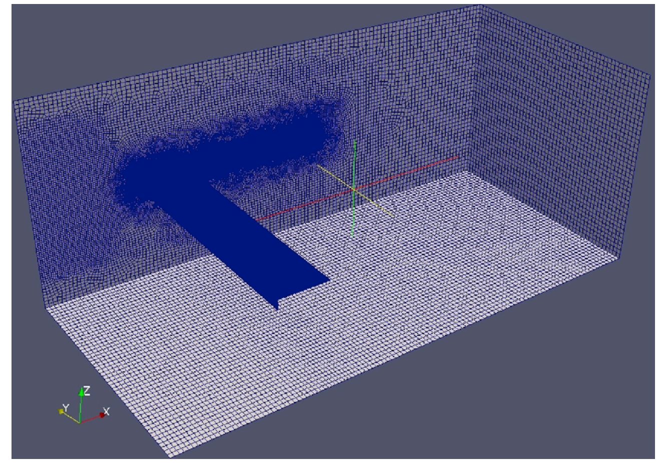

Fig. 3. The computational grid used in the 3D heaving simulation.

have shown their potential in modelling wind-induced responses and extracting aerodynamic and aeroelastic parameters such as flutter derivatives (Xiang and Ge, 2002; Owen et al., 2006; Sun et al., 2009; Waterson and Baker, 2010). Later, 3D simulations using Large Eddy Simulation (LES) models have become more available, focusing on uncovering the characteristics of the separation bubble, the effect of the after-body length on the separation and reattachment of the flow and the coherence structure of the surface pressure around a static rectangular cylinder (Bruno et al., 2010). LES simulations have also been coupled with structural solvers to model the fluid-structure interaction (FSI) of a 3D elastically supported rectangular cylinder and bridge deck section (Sun et al., 2008; Bai et al., 2013; Zhu and Chen, 2013). These researches highlighted the suitability of the LES model to capture the inherent unsteadiness in FSI problems and to maintain the flow structure in the wake region in contrast to the over-dissipation of the URANS models. Daniels et al. (2014) also applied this method to predict the effect of the

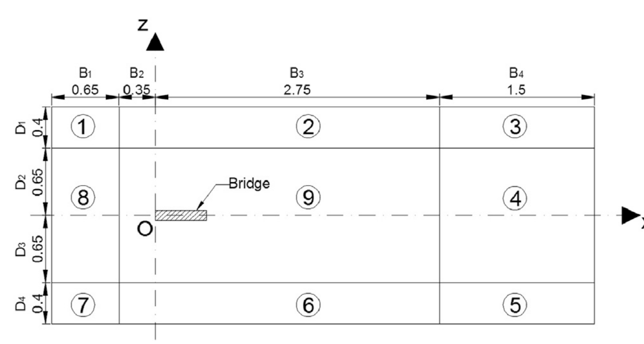

Fig. 4. Illustration of 9 different blocks in the computational domain; dimensions are in metres.

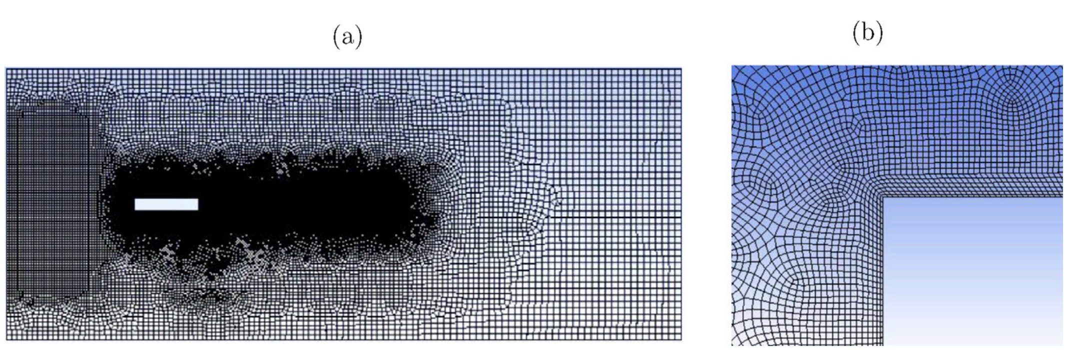

Fig. 2. The computational grid in the *x-z* plane (a) for the entire domain and (b) around the leading edge.