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Free-Stream Turbulence Effects on Long-Span Bridge Aerodynamics

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Abstract

The importance of vortex induced vibrations (VIV) in the design of bridge decks is becoming more apparent (Wu and Kareem, 2012). Generally, experimental literature presents a bridge deck situated in a smooth flow, though bridges are usually subjected to the inherent turbulence of atmospheric wind. According to the results of Matsumoto et al. (1993), the effects of turbulence on VIV are rather complicated, this is mainly due to an interaction between the vortices in the wake, and vortices induced by the structures motion. The impacts of turbulence on the motion-induced forces are uncertain due to a limited understanding of this issue. Wu and Kareem (2012) also present a conjecture, suggesting that turbulence can enhance or diminish the structural response, depending on whether the dominant vortices are generated from the motion of the structure, or vortex shedding in the wake. This numerical investigation aims to verify this hypothesis, while studying the effects of turbulence on the structural response, aerodynamic forces, correlations, and wake characteristics for a dynamic bridge deck. Some effects of freestream turbulence on a rectangular bridge deck undergoing VIV are presented. Heaving motion of the model under a smooth flow is presenting with a peak r.m.s. response y/D 3% in a close agreement with the equivalent wind tunnel experiment. Introducing turbulence into the flow reduces the peak rms response by 50%, which is in accordance with observations in the literature. This abstract also reports the effects of turbulence on the spanwise correlation of pressure on the bridge deck surfaces. Due to the dominance of the structural motion, the correlations for the dynamic cases at lock-in were markedly increased in comparison to the equivalent static case. The presence of turbulence has also shown to reduce the correlation across the span for both static and dynamic cases. It can therefore be deduced that turbulence reduces the strength of the leading edge (motion-induced) vortices of the structure, and accordingly its VIV response. Sensitivity studies of the effects of turbulence intensity and integral length scales were conducted. Effects of turbulence on the pitching motion were studied as well. Detailed results will be reported in the conference.

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Keywords: Synthetic inflow condition; large-eddy simulation; vortex-induced vibrations; spanwise-correlation; torsional flutter;

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1. Introduction

Vortex Induced Vibrations (VIV) of a bluff body is an important fluid-structure interaction phenomenon, and many of questions concerning its mechanism remain unanswered. Recently, a review paper by Wu and Kareem[20] describes a series of previous investigations on the VIV of bridge sections. A notable feature of this previous work

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is the enormous effort in determining the effects of the structure's geometry on the VIV response. For instance, a considerable amount of research concerns the circular cylinder, where the von Karman 'vortex street' is the main cause of the VIV. However, cross-sections typical of a bridge deck have a number of sources for a VIV response due to the presence of an after-body and the inherent asymmetric feature. While much of the literature has focused on the amplitudes incurred by VIV, comparatively few measurements are presented for the forces exerted on the body during lock-in. Therefore, further study would give a much deeper insight into the mechanism of VIV. At the same time, literature concerning the VIV response under a turbulent flow is scarce. Usually, literature presents a bridge deck situated in a smooth flow (typically with a turbulence intensity $< 1\%$). However, bridges operate in the turbulent atmospheric boundary layer. According to the results of Matsumoto et al.[12], the effects of turbulence on VIV are rather complicated, this being mainly due to an interaction between the vortices in the wake (von Karman), and vortices induced by the structure's motion.

According to Wu and Kareem[20], the impacts of turbulence on the motion-induced forces are uncertain due to a limited understanding of this issue. Compared to the investigations of a static case, studies of the effect of free stream turbulence on flow-induced vibration of spring mounted cylinders are scarce. Blackburn and Melbourne[1] investigated the forced heaving vibration tests of a cylinder immersed in turbulent flow with analysis for the correlation and phase angles of the coefficient of lift. Lin et al.[9] also carried out a similar investigation, considering a forced torsional oscillation. They subsequently report the effect on turbulence on the flutter derivatives, concluding that turbulence has a stabilising effect on flutter instability. More recently, So et al.[18] carried out a wind tunnel investigation, for the turbulent flow over a circular cylinder undergoing free vibration. They report a magnified response at lock-in under a turbulent flow, in comparison to smooth (or uniform) flow. Wu and Kareem[20] speculated that freestream turbulence can stabilize or destabilize the response depending on the relative intensity of the von Karman to the motion-induced vortices; if the von Karman vortices dominate, the presence of freestream turbulence would reduce the structural response and vice-versa. The cited papers in this section mainly consist of the experimental analysis for freestream turbulence effects on VIV. To the best of the authors' knowledge, analysis using a numerical approach is not reported in the literature.

Computational Fluid Dynamics (CFD) has become a powerful tool for the wind engineer. Most of the literature on the analysis of VIV at very large Reynolds numbers is limited to using a 2D domain. Fujiwara et al.[4] applied such analysis to the bridge deck of a H cross-section. Using the Arbitrary Eulerian Equations (ALE), their analysis showed that there is sudden change in lift and amplitude of the section at two distinct Reynolds numbers (i.e. 1000, 2400). A notable contribution is the work of Lee et al.[8]. In this work the cross-sections of the Namehae and Seohae bridge were analysed using Unsteady Reynolds Averaged Navier Stokes (URANS) turbulence modelling while subjecting the models to a forced vibration. Their results show a good agreement of the aerodynamic forces with the equivalent wind tunnel tests for the Namehae bridge, and with the test of structural response amplitudes for the Seohae bridge. More recently, Sarwar et al.[16] investigated the rectangular and box-girder cross-section, with and without fairings using Large Eddy Simulation (LES) implemented in ANSYS Fluent. Their work applied a forced vibration to the structure, focusing on the phase-angle changes, and lift force characteristics around the lock-in region. Their later work (Swarwar and Ishihara[19]) also presents the structural response for the free oscillations, though mainly focuses on the flow-field and aerodynamic characteristics for the forced motion. In this paper we examine the flow around a rectangular cylinder (assimilating a bridge deck) under smooth and turbulent flows while considering the underlying mechanisms affecting the VIV response.

This paper also considers the pitching motion of the structure, and the torsional flutter responses. Literature on numerically modelling the torsional responses of the bridge deck are scarce. The experimental measurements provide ample amount of deflection data but fail to report the associated aerodynamic forces. A notable contribution to torsional flutter is provided by Matsumoto (e.g. Matsumoto[11]). Matsumoto has clarified the effects of von Karman vortices on torsional flutter, such as torsional mitigation (Matsumoto et al.[13]). However, it must be noted that a large portion of this topic is still not understood yet, such as the characteristics of the aerodynamic forces at this occurrence, let alone the mechanism of von Karman vortices on the flutter stability. Hence, with the features associated with CFD, detailed analysis of pitching motion becomes more feasible.

2. Outline of CFD modelling

The focus of analysis surrounds a rectangular cylinder with aspect ratio 4. The calculations in this work were performed using the open-source code OpenFOAM 2.2.1 which previously has shown to be effective for simulating bluff body flows (Daniels et al.[3]) and obtaining force coefficients for bridge decks (Sarkic and Hoffer[15]). Large-Eddy Simulation was performed throughout this work with the Mixed Time Scale (MTS) subgrid-scale (SGS) model proposed by Inagaki et al.[5]. This SGS model has the feature of requiring no wall damping function. The constants associated with the MTS model, C_M and C_T, were specified as 0.05 and 10 respectively. These are in accordance with Inagaki et al.[5], who optimised these values for bluff body flows. A second order implicit scheme was used for the temporal discretisation and the bounded Gamma scheme was used for the convection term. For this scheme, the chosen value of β determines the blending between Central differencing and Upwind differencing. In this work, β was set as 0.1, as suggested by Jasak[6]. The PIMPLE algorithm was adopted for the velocity-pressure coupling, combining the SIMPLE and PISO algorithms. The momentum equation are solved repeatedly as outer iterations (SIMPLE), while pressure corrections are performed using the PISO algorithm. The number of outer corrections was set to 2, and the number of pressure correctors set to 3 in this study.

The dimensions of the computational domain were $66.6D \times 20D \times 13.3D$, with a recutangular cylinder placed at 24D from the inlet; D is the cylinder's thickness. A block-structured mesh was constructed. The y_1^+ of the cells around the surface of the cylinder was set to be within the range $y_1^+ < 5$ (i.e. equalent to $D/200$) with a growth rate of 1.05. The parameter, $\delta z/D$, has widely been used for cylinder flows, with δz being the grid size in the spanwise direction. Bruno et al.[2] varied this parameter between 0.05 to 0.21, while plotting the spanwise correlation. Their results show that a value of 0.21 produced a larger correlation of pressure around the leading edge, when compared to the equivalent experimental result. As modelling this region is crucial for the VIV response (e.g. Shiraishi and Matsumoto[17], Matsumoto et al.[14]), it is important to resolve the flow sufficiently. Bruno et al.[2] found that the spanwise correlation for the $\delta z/D = 0.1$ and 0.05 resolution showed little difference to the result. Therefore, to obtain an efficient calculation, the resolution $\delta z/D = 0.1$ was adopted for the present work.

For validation of the fluid-structure coupling method for the heaving motion, the characteristics of the flow were in accordance with those of the wind tunnel of Marra et al.[10]. A Dirichlet condition for the velocity field was applied to the inlet boundary. A uniform smooth flow ($I_u < 0.1\%$) was specified with the Reynolds number 40,000 (based on freestream velocity U at lock-in and the cylinder thickness D). A no-slip boundary condition was applied to the surfaces of the cylinder. For the outflow, a zero-gradient boundary condition was imposed. The symmetry boundary condition was prescribed for the ceiling and floor while periodic conditions were imposed to the lateral sides of the domain.

2.1. Freestream turbulence effects on the heaving and pitching response

The turbulence was generated using a divergence-free synthetic turbulence generation approach (Kim et al.[7]). In order to satisfy the divergence-free criterion during pressure-velocity coupling, Kim et al.[7] impose the synthetic turbulence downstream from the inlet boundary at a distance x_0. For the present work, $x_0 = B/2$. The turbulence generation approach requires a set of integral length scales, and turbulence intensity. To compare with the observations of Matsumoto et al.[12], the streamwise turbulence intensity ($I_1 = u'/U$) was specified as 6%. The integral length scales L_{ij} were defined as

$$L_{ij} = \int_0^{r_{ij,0.1}} C_i(r\hat{e}_j)dr, \qquad (1)$$

where $C_i(r\hat{e}_j)$ is the correlation function. The indices i and j indicate the velocity vector and directions respectively. $r_{ij,0.1}$ is the separation distance for function, which is set equal to 0.1. The integral length scale L_{11} was chosen to be $2B/3$; the components of pairs ($I_2 = v'/U$, L_{22}) and ($I_3 = w'/U$, L_{33}) were taken as 1/3 and 1/2 respectively of the corresponding component of the pair (I_1, L_{11}). These turbulence parameters are denoted as the 'base I_1, I_2, I_3' and 'base L_{11}, L_{22}, L_{33}' respectively for the turbulence intensities and length scales. The calculations were run with the same initialising and averaging time as the smooth flow cases.

2.2. Modelling of the free vibration

As this work focuses on the free vibration of the cylinder, a two-way coupling is required between the fluid and the structure. For an efficient calculation, a partitioned procedure was chosen. The fluid-structure algorithm was similar to that of a conventional-sequential-staggered (CSS) method. A similar approach has been implemented in Swarwar and Ishihara[19] for a forced oscillation using an Ordinary Differential Equation to prescribe the motion of the cylinder. In the present work, the response of the structure was calculated using a forced mass-spring-damper equation of heaving motion.

$$m(\ddot{y} + 2\zeta\omega_n\dot{y} + \omega_n^2 y) = \frac{1}{2}C_L(t)\rho_f U^2 B, \tag{2}$$

where m is the mass per-unit-length of the structure, ζ is the damping ratio, ω_n is the circular natural frequency of the structure in the vertical direction, ρ_f is the fluid density, U is the freestream velocity, and B is the streamwise length of the cylinder. The time-dependent lift coefficient $C_L(t)$ was obtained by integrating the pressure over the surface of the cylinder. Equation 2 is integrated for each time step using the Runge-Kutta-Fehlberg method. The calculated deflection was used for the dynamic mesh solver, which is discussed in §2.3.

2.3. Dynamic mesh

The term *dynamic mesh* refers to the relative distances among grid points changing in time to adjust to an unsteady motion of a body. This can be achieved through squeezing and stretching the surrounding cells and their associated vertices. For the finite volume method, the conservation equation of property, ϕ, over an arbitrary moving control volume, V_C, in integral form is

$$\frac{d}{dt}\int_{V_C}\phi dV_C + \int_A dA\cdot(\vec{u} - \vec{u}_b)\phi = \int_{V_C}\nabla\cdot(\Gamma\nabla\phi)dV_C, \tag{3}$$

where $\vec{u}$ is the fluid velocity vector, A is the cell-surface-normal vector and $\vec{u_b}$ is the boundary velocity vector of the cell-face. To govern the vertex motion, OpenFOAM adopts a Laplacian smoothing scheme, described by

$$\nabla\cdot(\gamma\nabla u_p) = 0, \tag{4}$$

where u_p is the point velocity, which is imposed at each vertex of the control volume. The boundary velocity u_b is interpolated from u_p. The boundary conditions for equation 4 are enforced from the known boundary motion, e.g. a moving wall. The vertex position at the time level $n + 1$ is calculated by using u_p,

$$x^{n+1} = x^n + u_p\Delta t. \tag{5}$$

The variable γ prescribes the distribution of deforming cells around the moving body. Ideally for the Laplacian approach, the cell distortion near the moving wall should be less perturbed by the motion of the body, while with increasing distance away from the wall, the cells should have a greater freedom to deform. Under this concept, the quadratic diffusion model ($\gamma = 1/l^2$) has shown to present a suitable distribution of cells around the body, with l being the distance from the moving wall. Hence, this model is adopted for the present work. As the grid motion in the whole domain is governed by equation 4, an interface between the static and dynamic mesh regions is not required.

3. Conclusions

The numerical analysis of a rectangular cylinder undergoing Vortex-Induced Vibrations (VIV) under smooth and turbulent flows is presented here. An appealing aspect of this work is the analysis of free-vibrations, as opposed to a forced one. The latter being more commonly reported in the literature, particularly for experimental analysis. The numerical approach was first validated by comparing the responses for 1DOF heaving and torsional motions to an equivalent wind tunnel experiment - with close agreement. Further investigation into the flow field at lock-in provided a deeper insight into the importance of the leading edge vortex shedding for both heaving the pitching motions. A synthetic turbulent inlet condition (Kim et al.[7]) was also utilised to analyse the VIV responses under turbulent flows. It was observed that the presence of freestream turbulence reduced the peak responses, with an evident sensitivity to the freestream turbulence intensity and integral length scale. This is unsurprising seeing the apparent close relation between spanwise correlation of the surface pressure and the incoming turbulence intensity and integral length scales.

At present the integral length scales of the freestream turbulence have been considered to be of the order of the cylinder dimensions. Investigations into larger length scales, to simulate the turbulence eddies observed in the atmospheric boundary layer is currently under investigation and will be presented in a future report.

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References

[1] H.M. Blackburn and W.H. Melbourne. Sectional lift forces for an oscillating circular cylinder in smooth and turbulent flows. *Journal of Fluids and Structures*, 11:413–431, 1997.

[2] L. Bruno, N. Cost, and D. Fransos. Simulated flow around a rectangular 5:1 cylinder: Spanwise discretisation effects and emerging flow features. *Journal of Wind Engineering and Industrial Aerodynamics*, 106-106:203–215, 2012.

[3] S.J. Daniels, I.P. Castro, and Z-T Xie. Peak loading and surface pressure fluctuations of a tall model building. *Journal of Wind Engineering and Industrial Aerodynamics*, 120:19–28, 2013.

[4] A. Fujiwara, H. Kataoka, and M. Ito. Numerical simulation of flow field around an oscillating bridge using finite difference method. *Journal of Wind Engineering and Industrial Aerodynamics*, 46-47:567–575, 1993.

[5] M. Inagaki, T. Kondoh, and Y. Nagano. A mixed time-scale sgs model with fixed model-parameters for practical les. *Journal of Fluids Engineering*, 127, 1-13 2005.

[6] H. Jasak. *Error analysis and estimation for the finite volume method with application to fluid flows*. PhD thesis, Thermofluids section, Department of Mechanical Engineering, Imperical College of Science, Technology and Medicine, 1996.

[7] Y. Kim, I.P. Castro, and Z-T. Xie. Divergence-free turbulence inflow conditions for large-eddy simulations with incompressible flow solvers. *Journal of Computers and Fluids*, 84:56–68, 2013.

[8] S. Lee, J.S. Lee, and J.D. Kim. Prediction of vortex-induced wind loading on long-span bridges. *Journal of Wind Engineering and Industrial Aerodynamics*, 46-47:587–594, 1997.

[9] Y-Y. Lin, C-M. Cheng, J-C. Wu, T-L. Lan, and K-T. Wu. Effects of deck shap and oncoming turbulence on bridge aerodynamics. *Tamkang Journal of Science and Engineering*, 8(1):43–56, 2005.

[10] A.M. Marra, C. Mannini, and G. Bartoli. Van der pol-type equation for modeling vortex-induced oscillations of bridge decks. *Journal of Wind Engineering and Industrial Aerodynamics*, 99:776–785, 2011.

[11] M. Matsumoto. Vortex effect on torsional flutter. In *The seventh Asia-Pacific conference on wind engineering*, Taipei, Taiwan, November 2009. APCWE-VII.

[12] M. Matsumoto, N. Shiraishi, S. Stoyanoff, and T. Yagi. Mechanism of, and turbulence effect on vortex-induced oscillations for bridge box girders. *Journal of Wind Engineering and Industrial Aerodynamics*, 49(1-3):467–476, 1993.

[13] M. Matsumoto, H. Shirato, T. Yagi, R. Shijo, A. Eguchi, and H. Tamaki. Effects of aerodynamic interferences between heaving and torsional vibration of bridge decks: the case of the tacoma narrows bridge. *Journal of Wind Engineering and Industrial Aerodynamics*, 91:1547–1557, 2003.

[14] M. Matsumoto, T. Yagi, H. Tamaki, and T. Tsubota. Vortex-induced vibration and its effect on torsional flutter instability in the case of b/d = 4 rectangular cylinder. *Journal of Wind Engineering and Industrial Aerodynamics*, 96:971–983, 2008.

[15] A. Sarkic and R. Hoffer. Improved numerical simulation of bridge deck aeroelasticity by model validation. In *6th European and African Conference on Wind Engineering*, Cambridge, UK, 2013.

[16] M.W. Sarwar, T. Ishihara, K. Shimada, Y. Tamasaki, and T. Ikeda. Prediction of aerodynamic characteristics of a box girder bridge section using the les turbulence model. *Journal of Wind Engineering and Industrial Aerodynamics*, 96:1895–1911, 2008.

[17] N. Shiraishi and M. Matsumoto. On classification of vortex-induced oscillation and its application for bridge structures. *Journal of Wind Engineering and industrial Aerodynamics*, 14(1-3):419–430, 1983.

[18] R.M.C. So, X.Q. Wang, W-C. Xie, and J. Zhu. Free-stream turbulence effects on vortex-induced vibration and flow-induced force of an elastic cylinder. *Journal of Fluids and Structures*, 24:481–495, 2008.

[19] M.W. Swarwar and T. Ishihara. Numerical study on suppression of vortex-induced vibrations of box girder bridge section by aerodynamic countermeasures. *Journal of Wind Engineering and Industrial Aerodynamics*, 98:701–711, 2010.

[20] T. Wu and A. Kareem. An overview of vortex-induced vibration (viv) of bridge decks. *Journal of Frontiers of Structural Civil Engineering*, 6 (4):335–347, 2012.