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On estimating the aerodynamic admittance of bridge sections by a mesh-free vortex method

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ABSTRACT

A stochastic method of generating a synthetic turbulent flow field is combined with a 2D mesh-free vortex method to simulate the effect of an oncoming turbulent flow on a bridge deck cross-section within the atmospheric boundary layer. The mesh-free vortex method is found to be capable of preserving the a priori specified statistics as well as anisotropic characteristics of the synthesised turbulent flow field. From the simulation, the aerodynamic admittance is estimated and the instantaneous effect of a time varying angle of attack is briefly investigated. The obtained aerodynamic admittance of four aerodynamically different bridge sections is compared to available wind tunnel data, showing good agreement between the two.

1. Introduction

In the design phase of large suspension bridges many resources are normally used to conduct extensive wind tunnel tests to prevent structural failure caused by aerodynamic forces. Various experimental methods are used to determine the influence of static, periodic and stochastic aerodynamic forces on the bridge, and how these excite certain structural responses of the bridge. Due to a required high structural stiffness, bridge decks are typically box-shaped and hence aerodynamically bluff bodies. The result is a highly complex flow around the bridge deck, which can cause a number of aero-elastic phenomena to occur under different conditions. Aerodynamically bluff bodies are generally more sensitive to flow separation, and thus a significant change in the aerodynamic forces may be observed when varying the angle of attack. Hence the effect of turbulence in the oncoming flow becomes important when evaluating the complete aerodynamic performance of the bridge section, as the turbulence results in a fluctuating effective angle of attack.

The effect of a turbulent oncoming flow on the aero-elastic interactions of the bridge is indeed non-trivial. On one hand the turbulent fluctuations of the flow will introduce a stochastic aerodynamic force which will disturb any periodic excitation and thus stabilise the bridge against flutter. On the other hand the stochastic fluctuations may themselves be a cause to unpredicted high aerodynamic forcing on the bridge. As turbulence consists of eddies of multiple scales that are transported by the flow, the sampled flow velocity at a fixed point will show a time history which contains a large band of frequencies at different energy levels. Therefore, with a strong analogy to ocean waves, situations occur where the turbulent eddies at different flow scales become instantaneously synchronised resulting in a fluctuation that is even larger than the amplitude of the largest eddies in the flow. When subject to such super-scale fluctuations the bridge section will experience sudden large change in the aerodynamic forcing and a vortex formation on the leading edge of the bridge may occur. Vortex formation on the leading edge is of significant concern as it produces strong gusts on the traffic lane which may be dangerous for large vehicles travelling on the bridge deck.

Prendergast and McRobie (2006) and Prendergast (2007) presented a vortex method to simulate an oncoming turbulent flow in bluff body aerodynamics. The flow was simulated using the Discrete Vortex Method (DVM) implementation VXFlow by Morgenthal (2002). The oncoming turbulent flow was implemented by synthesizing a time varying turbulent velocity field by a stochastic method, originally proposed by Shinozuka and Jan (1972), on the corner-points of a single column of mesh cells upstream of the bridge section. The circulation of each cell of the velocity field was then calculated and included in the DVM simulation by seeding the circulation as vortex particles throughout the simulation.

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Rasmussen et al. (2010) used a similar approach, based on the DVM implementation DVMFLOW by Walther (1994) and Walther and Larsen (1997), to obtain an extended aerodynamic analysis of the effect of a turbulent oncoming flow. Emphasis was placed on the spectral transfer functions between the turbulent velocity fluctuations of the oncoming wind and the resulting buffeting forces acting on the bridge section. This transfer function is referred to as the aerodynamic admittance function. Rasmussen et al. (2010) showed that the aforementioned method is able to successfully calculate the aerodynamic admittance function of a flat plate.

The concept of aerodynamic admittance employed in the present paper represents the chord wise filtering action of the solid deck section on the incoming turbulence. This definition is concordant with the two-dimensional (2D) classical assumption that the turbulent wind impacting onto a given span wise section creates aerodynamic forces proportional to the steady state load coefficients at this section only and as a consequence the span wise coherence of the aerodynamic forces is identical to the span wise coherence of the oncoming turbulence. Recent research has demonstrated that this is not the case for common bridge decks for which the span wise forces are found to be much more correlated than the oncoming turbulence although of less magnitude than expected from the classical assumption (Larose, 2003). Strip theory which splits the aerodynamic action of the turbulence in a chord wise (aerodynamic admittance) and a span wise component (root coherence of turbulence) is often employed in common commercial gust loading (buffeting) calculations for want of better models thus 2D aerodynamic admittance functions simulated in the present paper remain interesting to bridge designers.

In this paper, we extend the validation of the method of Rasmussen et al. (2010) towards a practical application in bridge aerodynamics. The aerodynamic admittance function of four different bridge sections are investigated and compared with available experimental data. The bridge sections which are shown in Fig. 1 represents a selection of the most common bridge deck types used in bridge design: the mono box bridge (Great Belt East bridge), the double deck truss bridge (Øresund bridge), the plate girder bridge (Busan–Geoje bridge) and the twin box bridge (Stonecutters bridge).

In this work only a brief outline of the method is presented and the reader is referred to Rasmussen et al. (2010) and Rasmussen (2011) for a detailed description and validation of the applied numerical method.

2. Numeric method

2.1. The discrete vortex method

The flow is simulated using the two-dimensional DVM implementation DVMFLOW by Walther (1994) and Walther and Larsen (1997). Here the velocity–vorticity formulation of the Navier–Stokes equation is solved in a Lagrangian frame of reference by simulating computational particles which represents an elementary distribution of vorticity referred to as a vortex blob. Hence, as vorticity is a material property which is advected with the flow, the particle position $\boldsymbol{x}_p$ is solved in the Eulerian frame of reference by

$$\frac{d}{dt}\boldsymbol{x}_p = \boldsymbol{v}(\boldsymbol{x}_p). \tag{1}$$

The velocity field $\boldsymbol{v} = (u, v, 0)$ is obtained from the vorticity field $\boldsymbol{\omega} \equiv \nabla \times \boldsymbol{v}$ by solving the inverted kinematic relation for an incompressible flow, where $\nabla \cdot \boldsymbol{v} = 0$, by which

$$\nabla^2 \boldsymbol{v} = -\nabla \times \boldsymbol{\omega}. \tag{2}$$

The vorticity only has the out-of-plane component in a 2D flow i.e. $\boldsymbol{\omega} = (0, 0, \omega)$. Eq. (2) is recognised as a Poisson equation and can thus be solved for an arbitrary point $\boldsymbol{x}_p$ using a Green's function solution

$$\boldsymbol{v}(\boldsymbol{x}_p) = \int_{\mathbb{R}^2} \boldsymbol{K}(\boldsymbol{x}_p - \boldsymbol{x})\,\omega(\boldsymbol{x})\,d\boldsymbol{x} \tag{3}$$

where $\boldsymbol{K}$ is the 2D Green's function for Eq. (2) which for a 2nd order Gaussian regularised vortex blob is given as

$$\boldsymbol{K} = -\frac{1}{2\pi r^2}\left(1 - \exp\left(-\frac{r^2}{2\epsilon^2}\right)\right)\begin{pmatrix} (y_p - y) \\ -(x_p - x) \end{pmatrix} \tag{4}$$

Here $r = |\mathbf{x}_p - \mathbf{x}|$ and ϵ is the blob radius which in the present implementation is related to the discretisation of the geometry by $\epsilon/\delta l = 2$ where δl is the length of the discretisation segment. For a particle discretisation Eqs. (3) and (4) can be combined as

$$\boldsymbol{v}(\boldsymbol{x}_p) = \boldsymbol{V} - \sum_{i=1}^{N_p} \frac{\Gamma_i}{2\pi r_i^2}\left(1 - \exp\left(-\frac{r_i^2}{2\epsilon^2}\right)\right)\begin{pmatrix} (y_p - y_i) \\ -(x_p - x_i) \end{pmatrix}. \tag{5}$$

N_p is the number of particles in the flow, $\boldsymbol{V} = (U, 0)$ is the free-stream velocity, and Γ_i is the circulation of the particles which super-positioned represents the integral of the vorticity field. To reduce the computational load, Eq. (5) is evaluated using the fast multi-pole method (Carrier et al., 1988).

The incompressible 2D Navier–Stokes equation is solved in the following velocity–vorticity form:

$$\frac{D}{Dt}\omega = \nu \nabla^2 \omega, \tag{6}$$

where ν denotes the kinematic viscosity of the fluid. It is seen that Eq (6) is a diffusion equation which may be solved by a stochastic random walk method (Chorin, 1973). Hence, the diffusion of vorticity (Eq. (6)) may be included in the trajectory equation (Eq. (1)) by introducing a random walk in which the trajectory equation

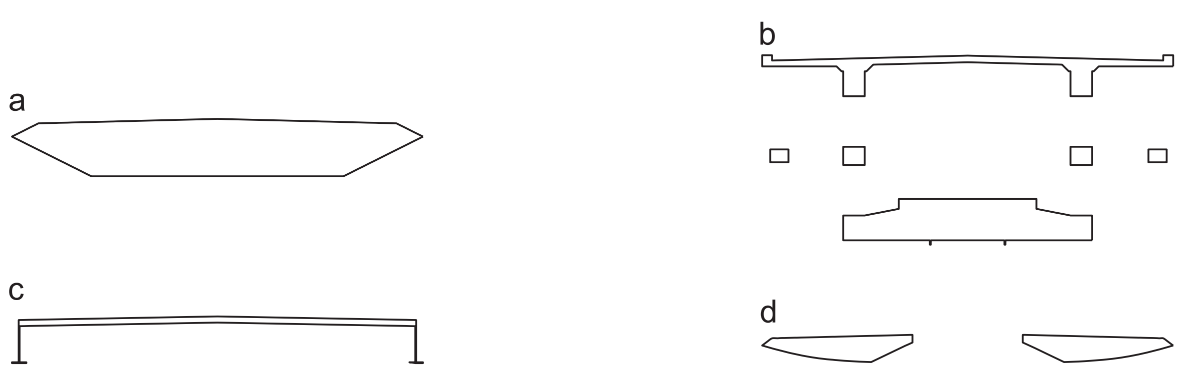

Fig. 1. Cross-sections of the four bridge decks (scaled to unity chord) which are investigated in the present study. (a) Great Belt East bridge, mono box girder bridge, (b) Øresund bridge, double deck truss bridge, (c) Busan–Geoje bridge, plate girder bridge, and (d) Stonecutters bridge, twin box girder bridge.