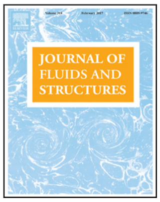
Journal of Fluids and Structures 72 (2017) 1–24

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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



Pseudo three-dimensional simulation of aeroelastic response to turbulent wind using Vortex Particle Methods

Khaled Ibrahim Tolba *, Guido Morgenthal

Bauhaus University Weimar, Chair of Modelling and Simulation of Structures, Marienstrae 13, 99423 Weimar, Germany

ARTICLE INFO

Article history:
Received 5 July 2016
Received in revised form 26 February 2017
Accepted 5 April 2017

Keywords:
Computational Fluid Dynamics
Vortex Particle Method
Wind-structure interaction
Buffeting
Multi-slice simulation
Long-span bridges
Stonecutters Bridge

ABSTRACT

This paper presents a numerical method for analysing the aero-elastic response of bluff line-like structures subjected to turbulent wind. Simulating the buffeting response of line-like structures such as bridges and towers requires accurate modelling of atmospheric turbulence, the cross-sectional aerodynamic behaviour and the structural dynamics. Here the fluid–structure interaction problem is solved considering a three-dimensional structural model coupled with a series of two-dimensional Computational Fluid Dynamics simulation slices, utilising the Vortex Particle Method. The coupled set of simulation slices accounts for the three-dimensional dynamic characteristics of the structure and the turbulent inflow conditions. This pseudo three-dimensional approach is presented as an accurate, yet computationally cheaper alternative to fully three-dimensional simulations of the fluid–structure interaction problem. For the inflow conditions in each simulation slice, the characteristics of the turbulent wind are modelled through pseudo-random velocity time-histories that satisfy the mean velocity profile, spectral properties and spatial coherence of the three-dimensional turbulent wind assumed. The wind field is modelled through vorticity injected at the upstream boundary of the simulation domain. The different components of the method are presented and validated. Finally, the method is applied to the study of a cable-stayed bridge, and the results are validated against wind tunnel measurements.

1. Introduction

The local atmospheric wind conditions that a structure is subjected to are determined by the global climatic effects as well as those of the local terrain. These wind properties constitute the inflow conditions of the wind-structure interaction problem that needs to be analysed in order to simulate the structural response to natural wind conditions. For flexible light-weight structures the fluid–structure interaction can result in significant dynamic structural response, which needs to be carefully considered e.g. in the design phase of long-span bridges. The relevant excitation phenomena can be categorised into two groups: aero-elastic instabilities such as flutter and limited amplitude oscillations. The former is a self-excitation due to motion-induced forces and may lead to collapse of the structure, whilst the limited amplitude response may be due to vortex-induced resonant vibrations (VIV) or buffeting. Buffeting is the aerodynamic response of the structure induced by the unsteady velocity fluctuations originating from the atmospheric turbulence in the wind.

In a practical design context, the relevant phenomena are often studied separately through semi-empirical models commonly based on linearised Aerodynamic Derivatives (Scanlan and Tomko, 1971) which are typically determined

---

* Corresponding author.
E-mail address: khaled.ibrahim.tolba@uni-weimar.de (K. Ibrahim Tolba).

http://dx.doi.org/10.1016/j.jfluidstructs.2017.04.001
0889-9746/

in laminar flow conditions for predicting the flutter limit and buffeting analysis performed using steady-state section aerodynamics with simplified admittance properties.

This paper introduces a numerical scheme which allows to simulate the response of complex line-like structures such as towers, masts and bridges by accounting for the following effects: (1) three-dimensional structural geometry, including changes in cross sectional geometry, (2) full linear dynamic behaviour of the structure through modelling an arbitrary number of modes of the structure and (3) turbulent wind properties. The scheme resolves the actual flow physics of the fluid–structure interaction processes at cross section level and hence is capable of also replicating complex interactions of the above phenomena, such as the effect of turbulence on VIV and multi-modal contributions to flutter instabilities. The focus of this paper, however, is on the buffeting response. Since buffeting is a complex interaction between the dynamic characteristics of the structure and the fluid flow originating from natural wind, accurate modelling of the induced wind is essential and forms a central part of the paper. Under the effect of this oncoming wind, the local section aerodynamics is resolved using the Vortex Particle Method (VPM).

The VPM (Ge and Xiang, 2008; Janjic et al., 2009; Larsen and Walther, 1997; Morgenthal, 2005; Taylor and Vezza, 2009; Walther and Larsen, 1997; Zhou et al., 2002) has been shown to be highly computationally efficient for two-dimensional simulations of the Navier–Stokes equations of slightly viscous flows. The efficiency arises from the discretisation of the vorticity through particles, which is naturally created on the surface of the structure and confined to a relatively small zone comprising boundary layer and wake. The method in its formulation with free-space boundary conditions has hence found wide application in bridge aerodynamics for two-dimensional section models, a similar concept to the section models used in wind tunnel testing. Two-dimensional reduction is particularly useful in the aerodynamic assessment of line-like structures such as bridges and high-rise buildings. Nevertheless, amongst others, the challenge of studying a structure with varying cross section along its axis requires an extension of the sectional analysis concept.

A pseudo three-dimensional simulation methodology is adopted here as a numerical approach within which multiple two-dimensional simulations are carried out. The two-dimensional sections are linked together via the structural properties, as well as the correlated inflow wind velocity, which is an input to each of the different sections as shown in Fig. 9. The turbulent wind is modelled as an inflow condition to the VPM, where the turbulence characteristics are correlated between the multiple layers, thus representing a pseudo three-dimensional oncoming wind field. The dynamic behaviour of the structure along its length is simulated through time integration in mode space. The coupling of fluid and the structural dynamics is done at every time step through the aerodynamic forces of the sections. Those are calculated by integrating the pressure on the surface of the section and applied to the mode-generalised structural dynamic time-stepping analysis model.

To sum up, the approach presented in this paper to simulate the buffeting response of bridges can be broken down to the following components:

1. two dimensional Computational Fluid Dynamics (CFD) simulation using VPM, for complex geometries, e.g. bridge cross-sections with guide vanes and railings,
2. a fully coupled set of multi-slice 2D CFD simulation domains in order to model the three-dimensional fluid–structure interaction (FSI) phenomena,
3. modelling of the oncoming turbulence in each of the 2D simulation planes using VPM. A pseudo 3D turbulence field is modelled via correlated turbulence inflow in each CFD slice.

The VPM method for 2D simulations of bluff body flows is widely used in research and practice, e.g. (Cottet, 1990; Larsen and Walther, 1998; Ploumhans and Winckelmans, 2000; Rossinelli et al., 2015; Smith and Stansby, 1988; Taylor and Vezza, 2001).

The multi-slice approach for modelling FSI problems of slender line-like structures was previously presented by Li et al. (2001), employing Large Eddy Simulation (LES) and the Finite Difference Method to simulate wave current interaction with vertical structures. Likewise, (Belver et al., 2012) employed a Lagrangian–Eulerian approach to investigate the vortex-induced vibrations (VIV) on line-like structures, also utilising a grid-based method. The multi-slice approach was then adopted by Morgenthal et al. (2014); Willden and Graham (2001); Yamamoto et al. (2004) for application of the mesh-free VPM method, thus encompassing the advantages of VPM for complex geometries as well as that of the quasi 3D approach.

The VPM simulation of oncoming turbulence, but for purely two dimensional simulations, was presented by Prendergast (2007). The method was validated and applied by Rasmussen et al. (2010) to simulate the aerodynamic admittance on a flat plate cross section.

The novelty of the current work involves the modelling and simulation of the oncoming turbulence in a pseudo 3D coupled multi-slice approach. This allows, for the first time, to resolve the intricate buffeting phenomena whilst using the advantages of the VPM method in resolving complex geometrical details at a low computational cost. As a crucial building block of this work in Section 4 the characteristics of the 3D turbulence field are validated before applying it to the FSI simulations. The proposed method offers a computationally cheaper alternative to fully three-dimensional simulations of wind engineering problems involving complex structures, which will continue to be impractical for the foreseeable future.