



Downburst-induced transient response of a long-span bridge: A CFD-CSD-based hybrid approach

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ABSTRACT

The long-span bridges, frequently located in the coastline and mountainous areas, are prone to suffering from the transient downburst winds associated with the thunderstorms. Therefore, it is important to examine the behaviors of long-span bridges under such wind events. In this study, the time history of non-turbulent downburst wind field is modeled using the impinging jet-based computational fluid dynamics (CFD) approach. It has demonstrated high-fidelity simulations of the downburst wind field, especially for the near-surface radial winds that are particularly significant for present investigation of bridge aerodynamics and aeroelasticity, with a reasonable computational cost. The simulated time-varying mean wind velocity field of a typical downburst event is validated using available field measurements. The correlated nonstationary fluctuations of the downburst are stochastically simulated by the Hilbert-wavelet scheme based on full-scale data, and then superimposed onto the CFD-based transient mean wind field. The obtained turbulent downburst wind field is employed as the dynamic inputs to the line-element-based three-dimensional (3-D) finite element model of the long-span bridge, and its downburst-induced transient response is acquired using the computational structural dynamics (CSD) approach. The aerodynamic and aeroelastic couplings between the downburst winds and the long-span bridge are modeled using the two-dimensional (2-D) indicial response functions that could well represent the transient bridge aerodynamics under non-synoptic winds. The time-domain buffeting response analysis of a long-span suspension bridge under the traveling downburst has been carried out utilizing the CFD-CSD-based hybrid methodology. The results highlight the importance of the transient and nonstationary effects on the non-synoptic wind-induced structural dynamic response.

1. Introduction

The non-synoptic wind events such as downbursts present violent impacts on the civil infrastructures in the atmospheric boundary layer. A number of researchers have demonstrated the importance of the non-synoptic wind events on the structural design (e.g., Holmes, 1999; Choi, 1999; Letchford et al., 2002; Qin et al., 2006; Hamada et al., 2010; Elawady et al., 2017). Actually, the design wind speeds with relatively high return periods are usually dominated by the thunderstorm downbursts (Twisdale and Vickery, 1992; Solari et al., 2015). The long-span bridges are frequently located in the coastline and mountainous areas to cross over straits, rivers and deep valleys. It is well known that the coastline regions are prone to suffering from the thunderstorm downbursts spawned by typhoons/hurricanes. Recent studies also show the thunderstorm downbursts or downburst-like winds are constantly

observed in the mountainous districts (e.g., Huang et al., 2016). While the design of the long-span bridges in thunderstorm-prone sites could employ a high extreme wind speed derived from the mixed climates (Gomes and Vickery, 1978; Cook et al., 2003), current consideration is limited to the straight-line winds of the neutral atmospheric boundary layer (Cao and Sarkar, 2015). Whereas the thunderstorm downbursts generate non-synoptic winds presenting time-varying mean values and nonstationary turbulence. It is unlikely that the downburst winds will result in aerodynamics instabilities (e.g., flutter or vortex-induced vibration) of bridges due to their transient nature and hence a lack of “build-up” time of structural dynamics (Chen, 2014; Hao and Wu, 2017). On the other hand, the long-span bridge may experience significant forced vibration (loss of serviceability) resulting from the transient wind loading during a downburst event.

The buffeting response analysis of the long-span bridge under a

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thunderstorm downburst requires the accurate inputs of low-level wind field. The basic characteristics and structures of downbursts have been well studied based on the early programs of “Northern Illinois Meteorological Research on Downbursts” and “Joint Airport Weather Studies” motivated by air carrier accidents during take-off and landing (McCarthy et al., 1982; Fujita, 1985) or on the more recent projects of “Wind and Ports” and “Wind, Ports and Sea” motivated by safe management of port areas (Solari et al., 2012, 2016). However, field measurements of wind velocities are still very limited due to the small temporal and spatial scales of the unpredictable downburst events (Hjelmfelt, 1988). The issue of low-resolution wind measurements in space has also been experienced in the laboratory experiments of downbursts. In addition, the Reynolds number effects is a considerable issue in the physically small-scaled simulations (Wood et al., 2001; Chay and Letchford, 2002; Sengupta and Sarkar, 2008). The large-scale facility Wind Engineering Energy and Environment (WinEEEE) Dome at Western University, Canada offers the unique opportunity to investigate the Reynolds number effects on the physically simulated downbursts (Hangan, 2014; Jubayer et al., 2018). Although the existing analytical models of downbursts offer a simplified and direct way to generate enough wind inputs for the buffeting response analysis of a long-span bridge, they are essentially derived from the incompressible Euler equations with an empirical representation of the turbulent boundary layer (Oseguera and Bowles, 1988; Vicroy, 1991; Li et al., 2012). Hence, these semi-empirical models cannot capture the downburst unsteady features associated with massive flow separations and reattachments. To obtain the high-resolution, high-fidelity wind field for accurate load estimation on structures, the computational fluid dynamics (CFD) technique has been extensively utilized to simulate the downbursts.

Several CFD-based schemes have been introduced to generate winds in the stationary downbursts such as the microphysics-based full-cloud model (Proctor, 1987a; 1987b; Hjelmfelt et al., 1989), cooling source-based sub-cloud model (Anderson et al., 1992; Mason et al., 2009; Vermeire et al., 2011) and impinging jet model (Selvam and Holmes, 1992; Chay et al., 2006; Kim and Hangan, 2007; Sengupta and Sarkar, 2008; Aboshosha et al., 2015; Sim et al., 2016). In addition, the CFD simulations of the moving downbursts have been advanced by a few researchers based on these models (e.g., Mason et al., 2007a; Li et al., 2009). In this study, the impinging jet model will be employed since it has demonstrated high-fidelity simulations of the downburst wind field, especially for the near-surface radial winds that are particularly significant for present investigation of bridge aerodynamics and aeroelasticity, with a reasonable computational cost. The impinging jet-based CFD approach can only acquire large-scale mean winds of the downburst, however, the turbulent fluctuations may play a significant role in buffeting response of a long-span bridge. Observations in the downburst events show time-dependent power spectral density (PSD) of the wind data (Wang et al., 2013). Hence, the downburst turbulence here will be synthesized using a recently developed Hilbert-wavelet nonstationary scheme (Wu, 2015; Wang and Wu, 2018). While the simulation of turbulent downburst wind field is based on the CFD scheme combined with the Hilbert-wavelet method, the computational structural dynamics (CSD) based on a finite element (FE) model will be utilized to numerically obtain the buffeting response of the long-span bridge. Specifically, the line-element-based three-dimensional (3-D) FE model with equivalent sectional properties, which could well capture the global dynamic behaviors of bridges, is employed.

The downburst-induced transient buffeting response of long-span bridges can be treated as a typical fluid-structure interaction (FSI) problem, where the interaction between the downburst winds and the long-span bridge could be captured using strongly coupled techniques (Farhat et al., 2003). However, the fully-coupled three-dimensional (3-D) FSI simulations at relatively high Reynolds number for the large-size, flexible, bluff structures is not easy to achieve using available computational resources. As a result, the conventional time-domain buffeting response analysis of bridges is based on the linear reduced-order

modeling with one-dimensional (1-D) aerodynamic indicial response functions (Béliveau et al., 1977; Chen et al., 2000; Wu and Kareem, 2014), and the coupling between the structural vibrations and wind field is achieved with 1-D aeroelastic indicial response functions (Scanlan et al., 1974). This semi-empirical, linearized analysis framework of bluff-body aerodynamics and aeroelasticity has been widely utilized for bridge buffeting response under stationary winds. Recent studies indicate that the transient nature of the downburst events could introduce an additional time scale in the wind-bridge interaction system, and hence the conventional 1-D indicial response function needs to be extended to a 2-D case (Hao and Wu, 2017). The 2-D indicial response functions developed by Hao and Wu (2017) could well represent the transient bridge aerodynamics under non-synoptic winds, and will be employed in this study. Accordingly, the time-domain buffeting analysis of a long-span suspension bridge under the traveling downburst will be carried out utilizing the CFD-CSD-based hybrid methodology to investigate the transient and nonstationary effects on the non-synoptic wind-induced structural dynamic response.

2. Impinging jet model-based CFD scheme

The open source CFD software OpenFOAM is employed to simulate both stationary and moving 3-D downbursts, where the spatial domain is discretized utilizing Finite Volume Method (FVM). Hence, the 3-D computational domain consists of a set of discrete, non-overlapped, control volumes. The values of independent variables are stored at the centers of control volumes, and the fluxes at surface of the control volumes are based on the interpolation of cell-center values (Jasak et al., 2007; Wu and Kareem, 2015). The downburst winds are regarded as incompressible, and essentially simulated with the Reynolds Averaged Navier-Stokes (RANS) model. As a result, the governing formulas derived from the Navier-Stokes equations are shown as:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} (U_i U_j) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \nabla^2 U_i - \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

where $i, j = 1, 2, 3$; U_i and p are the averaged wind velocity and pressure fields, respectively; t denotes the time; x_i and x_j represent the space coordinate; ρ is the air density; ν is the kinematic viscosity of the air; τ_{ij} is the Reynolds stress tensor to be determined using the Boussinesq's eddy-viscosity hypothesis with a two-equation turbulence model in this study.

2.1. Stationary downburst simulation

2.1.1. Numerical set-up

The 3-D stationary downburst simulation is utilized to validate the CFD schemes, which will be extended to the moving case in Sect. 2.2. To this end, the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm is chosen to solve the steady-state RANS equations, and the turbulence is modeled using the shear stress transport (SST) $k-\omega$ scheme (Menter, 1994). According to Mason et al. (2007b), the SST $k-\omega$ turbulence model presented an excellent performance in the simulation of the impinging jet flow. The second-order discretization schemes are applied for approximation of the gradient, convective and laplacian terms. A 3-D cylindrical computational domain is employed in the simulation, where the size is chosen as $16D_j \times 4D_j$ for the radial and vertical dimensions, respectively. The diameter of jet inlet, D_j , is set as 1 km, which is a typical size of the measured downbursts (Holmes et al., 2008). The central cross-section of the computational domain and its structured mesh are illustrated in Fig. 1. The inflow boundary is located at the nozzle of the impinging jet, and the height of the nozzle H is set as $2 \times D_j$ from the ground. The used nozzle height is in accordance with the

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