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An analytical model for simulating steady state flows of downburst

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ABSTRACT

Downburst wind events represent the greatest threat to many structural engineering systems due to the extreme wind that they generate. They have been shown to be the cause of many past failures of many structural systems. There are many experimental and numerical models for simulating these types of loads. However, analytical and empirical simulation models are needed to facilitate the analysis of structural systems under these types of loads. There are remarkable disparities between the available analytical models and the recorded field data, experimental and numerical simulations. Added to that, the effects of nonlinear growth of boundary layer thickness are rarely included in these models. This paper presents an analytical model that successfully matches the recorded field data, experimental and numerical results. Two new empirical functions which are able to simulate the radial and vertical profiles of horizontal downburst wind speed have been developed. These two equations have then been implemented into the continuity equation and the vertical and radial profiles of the vertical downburst wind speed have been estimated analytically. Once boundary layer effects have been included in the model, the radius corresponding to maximum wind speed becomes a function of elevation, the height corresponding to maximum wind speed becomes a function of the radial coordinates and the shapes of the speed profiles become changeable with the radial and vertical coordinates.

1. Introduction

Wind loads represent the prevalent critical loads for many structural systems such as transmission towers. Dempsey and White (1996) recorded that more than 80% of all failures of transmission towers around the world result from high intensity winds, ranging from the different forms of microburst and downbursts to fully mature tornadoes. For example, the failure of 19 transmission towers was reported during a microburst event in Manitoba, Canada in 1996 (McCarthy and Melsness, 1996). Similarly, Li (2000) reported that more than 90% of transmission tower failures in Australia are due to severe thunderstorms involving downburst events and Zhang (2006) recorded the failure of 75 transmission towers due to the strong wind events such as downburst and tornadoes in China in 2005.

The formation and extension of downburst winds are different from those of boundary layer winds. Downbursts occur when warm air rises and ascends above the cloud, creating a dome of warm air. The air cools at this height and then begins to fall, collapsing the dome and rushing back to the ground, forming an outburst of damaging air ('Downbursts' of air are called danger to aircraft, 1979).

Downburst wind speed and the associated loads acting on structural systems vary with downburst parameters such as downburst width, coordinates of the centre of the downburst relative to the centre of the structural system, downflow velocity and so on. In addition, each element in the structural system has different downburst parameters that produce maximum internal forces in those elements (Shehata et al., 2008). Investigation of structural systems under downburst loads is so complex that analytical and empirical models for simulating these types of loads are necessary to facilitate the analysis and design of structural systems subjected to them.

Earlier researchers presented several analytical and empirical models of wind speeds for simulating downburst wind loads. Oseguera and Bowles (1988) developed the first analytical model for non-turbulent downburst wind speed. They proposed that the vertical and horizontal components of downburst wind speed could be estimated by multiplying the vertical and horizontal shaping functions for each component. They developed a pair of shaping functions that were able to simulate velocity profiles of terminal area simulation systems (TASS) (Proctor, 1987), and employed the mass continuity equation for deriving the corresponding pair of shaping functions. Vicroy (1991) studied the previous model and improved the radial shaping function of horizontal wind speed and then improved the vertical shaping function of horizontal wind speed Vicroy (1992). However, there is still a significant difference between these models and the available field and numerical data.

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Nomenclature

D	diameter of downburst (m)
$f(r)\{p(z)\}$	radial {vertical} shaping function of the horizontal wind speed
$f_m(r)\{p_m z\}$	radial {vertical} shaping function of the maximum horizontal wind speed
$g(r^2)\{q(z)\}$	radial {vertical} shaping function of the vertical wind speed
R_c	characteristic length scale in Holmes' and Li et al.'s models
r,ϕ,z	cylindrical coordinates
r_m	radius at the overall maximum horizontal speed (m)
$u\{w\}$	wind speed in the radial {vertical} direction (m/s)
$u_{\max}$	magnitude of overall maximum horizontal speed (m/s)
$u_{m,rs}(r)\{u_{m,vs}(z)\}$	radial {vertical} shaping function of the maximum horizontal wind speed in Li et al.'s models
w_{jet}	jet speed (m/s)
$w_{\max}$	magnitude of maximum vertical speed (m/s)
w_0	vertical speed at the centre of downburst (m/s)
w_{0m}	vertical speed at the centre of downburst at altitude of peak horizontal speed (m/s)
z_h	depth of outflow (m)
z_m	height at the overall maximum horizontal speed (m)
z^*	altitude at which the magnitude of horizontal speed is half the peak speed (m/s)
v	tangential speed in radial coordinate (m/s)
$\xi_1,\xi_2,c_1,c_2,\gamma,\beta,\delta,\varepsilon,\kappa,\chi,A,B,C,\eta,\iota,\varphi$	non dimensional parameters
λ	scaling factor (s^{-1})

Holmes and Oliver (2000) presented an empirical function for simulating the radial profile of horizontal wind speed at 10 m height. Their function is more accurate in depicting the profile of downburst wind speed, but it is limited to the radial profile of horizontal wind speed. Wood et al. (2001) introduced an empirical function for simulating the vertical distribution of horizontal wind speed. Sengupta and Sarkar (2008) improved Wood et al.'s (2001) function by enhancing its parameters. The two empirical functions of Holmes and Oliver (2000) and Wood et al. (2001) matched the available field and numerical data, but they are limited to the horizontal downburst wind speed.

Chay et al. (2006a) improved the previous analytical model of Oseguera and Bowles (1988) and Vicroy (1991) by introducing several modifications to the model parameters. They also recommended adding the boundary layer effects through developing the height corresponding to maximum wind speed to become a function of distance from downburst centre. Again, Chay et al. (2006b) developed the shaping function of the vertical distribution of horizontal wind speed by replacing the radial shaping functions of the horizontal velocity by Wood et al.'s (2001) function. But they did not consider the continuity equation which controls the relation between the vertical and the horizontal speed.

Li et al. (2012) upgraded the earlier Oseguera and Bowles (1988) and Vicroy (1991) model by implementing the previous two empirical equations of Holmes and Oliver (2000) and Wood et al. (2001) to the continuity equation and then developed the corresponding equations for the vertical wind speed. However, the developed formula for vertical wind speed cannot be expressed in terms of elementary functions and so is complex to use. They inserted the nonlinear effects of boundary layer growth to the model by improving two empirical equations that are able to depict the variations in the horizontal and vertical coordinate of maximum horizontal wind speed. Their model was able to depict the profiles of horizontal wind speed including nonlinear effects of boundary layer growth, but failed to depict the variation of profiles of vertical wind speed and did not satisfy the continuity equation which confirms the relationship between the vertical and the horizontal downburst wind speed.

This study provides answers for the issues in the previous models by introducing a new pair of shaping functions that are able to simulate profiles of downburst wind speed and match the available field and numerical data with high accuracy. The vertical and radial profiles of vertical wind speeds have been estimated by using Euler and mass continuity equations and the new functions are characterized by their simplicity and simple integration. The nonlinear effects of boundary layer growth on the coordinates of the maximum wind speed have been included without dropping the continuity equation, and the changes in the shapes of the profiles due to the boundary layer effects have been introduced.

2. Model development

Oseguera and Bowles (1988) and Vicroy (1991) developed an analytical model for simulating downburst wind loads by solving the mass continuity equation and assuming a pair of shaping functions which were able to simulate velocity profiles at the altitude and the radial position of the maximum speed (Proctor, 1987). Their model has been summarised in the Appendix. In this study, their previous model will be derived again but the selected shaping function for the vertical and radial profile of the horizontal wind speed will be improved.

2.1. Shaping function for the vertical profile of the horizontal wind

The shaping function for the vertical profile of the horizontal wind speed for the models of Oseguera and Bowles (1988), and Vicroy (1992) has a remarkable difference with radar observation by Hjelmfelt (1988) and the recent experimental and numerical simulation results for downburst wind by Wood et al. (2001), Kim and Hangan (2007), Sengupta and Sarkar (2008) and McConville et al. (2009). Wood et al. (2001) developed the following empirical equation which matches their numerical and experimental results:

$$u(z)=A\left(\frac{z}{z^*}\right)^B\left[1-\mathrm{erf}\left(C\frac{z}{z^*}\right)\right] \quad (1)$$

where erf is the error function, the parameters A, B and C are 1.55, 1/6 and 0.7, respectively and z^* is defined as the altitude at which the magnitude of horizontal speed is half the maximum speed. The elevation z^* can be expressed in terms of z_m where z_m is the height of the maximum horizontal wind speed. It has been stated that z^* is in the range of 6.0 z_m (Wood et al. 2001). This model matches field, experimental and numerical data better than the Oseguera and Bowles (1988) and Vicroy (1991) models that have a significant difference between the available data, in particular, for heights less than z_{m}. Sengupta and Sarkar (2008) improved the parameters A, B and C to be 1.52, 1/6.5 and 0.68, respectively. Li et al. (2012) revised the model parameters, estimated implicit relationships between the parameters and developed a simple