J. Wind Eng. Ind. Aerodyn. 129 (2014) 49–63

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Empirical models for predicting unsteady-state downburst wind speeds

El-Sayed Abd-Elaal, Julie E. Mills*, Xing Ma

School of Natural and Built Environments, University of South Australia, Australia

ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form
15 March 2014
Accepted 20 March 2014
Available online 17 April 2014

Keywords:
Downburst
Temporal profiles
Intensity decay function
Analytical simulation
Empirical simulation

ABSTRACT

Recent reports of failures of transmission line systems in several regions around the world point to downburst events rather than other types of thunderstorms as the primary cause of failure. Downburst winds are becoming the governing type of design wind event in many areas around world. There is an essential need for developing analytical or empirical models to apply these types of loads to structural systems. Most of the available models, whether analytical or empirical, are restricted to steady state downburst flow and do not consider the changes in wind speeds with time. Downburst wind speeds continuously change with time through the life cycle of the event. The current study uses estimated ages for downburst events from several recorded field events combined with numerical simulation to establish a pair of intensity decay functions. These functions have the ability to depict the changes in the temporal profile of wind speeds with space and can be added to the earlier empirical and analytical steady state models to update them from steady state to unsteady state “time dependent” simulation. Once the parent storm speed has been determined and added to the model, a full scale transient downburst wind speed model in the 4-dimensions is developed. Finally, several field cases are studied to show the application and accuracy of the presented model.

1. Introduction

Downbursts are the most common cause of severe winds (Chay et al., 2006a) and represent the highest wind speeds at 10 m height in several areas around the world (Holmes, 2002). Downburst events have interested researchers for several decades up to the present, due to their importance for structural engineering, wind farm and industrial aviation (Byers et al., 1946; Wilson et al., 1984; Proctor, 1987a, 1987b; Hjelmfelt, 1988; Fujita, 1990; Chen and Letchford, 2004, 2006; Selvam and Holmes, 1992; Holmes et al., 2008; Lin and Savory, 2006; Mason et al., 2009, 2010; Vermeire et al., 2011a, 2011b; Wang et al., 2013; Lombardo et al., 2014)

These types of thunderstorms have been simulated by different types of models: physical, numerical and analytical. The early work on simulating this phenomenon was introduced by Glauert (1956) who noted that downburst flow could be simulated by the flow produced by a vertical take-off aircraft, then Bakke (1957) who started an earlier experimental simulation for a wall jet. Holmes (1992) and Cassar (1992) employed a wind tunnel for modelling downburst wind loads, Wood et al. (2001) applied the impinging jet model on different embankment heights as well as on different roughness surfaces and Chay and Letchford (2002) studied the profiles of downburst winds using a stationary wall jet tunnel then a moving downburst wind tunnel experiment (Letchford et al., 2002). Hangan et al. (2003) studied different scales for downburst wind models and concluded that the impinging jet simulations are scale dependent, while Xu and Hangan (2008) examined the different downburst parameters of cloud-base height, scale, boundary conditions and terrain roughness. Further researchers worked on developing numerical simulation models, starting from Proctor (1987a) who developed an early numerical simulation for downburst flow, then Selvam and Holmes (1992) who developed a numerical simulation using a K-epsilon turbulence model. Kim and Hangan (2007) introduced a numerical simulation for steady and unsteady state using impinging jets for application to downbursts, Mason et al. (2009) simulated downburst storms by utilising a cooling source model, Vermeire et al. (2011a) compared the impinging jet models with the cooling source models and Orf et al. (2012) simulated downburst using a very high-resolution 3D cloud model.

Others have developed analytical and empirical models to facilitate the application of these loads during structural analysis and for industrial aviation. The earlier generations of these models are concentrated on depicting the vertical and radial distribution of the downburst flow at the location of the maximum horizontal speed (Oseguera and Bowles, 1988; Vicroy, 1991, 1992; Holmes and Oliver, 2000; Chay et al., 2006a). The first analytical model for simulating downburst wind speed was introduced by Oseguera and Bowles (1988). They developed a pair of shaping functions that were able to simulate velocity profiles of terminal area simulation systems (TASS) at locations of maximum horizontal

* Corresponding author. Tel.: +61 883023073.
E-mail address: julie.mills@unisa.edu.au (J.E. Mills).

http://dx.doi.org/10.1016/j.jweia.2014.03.011
0167-6105/

speed (Proctor, 1987a), and then their pair of shaping functions were improved by Vicroy (1991, 1992). Holmes and Oliver (2000) developed an empirical model for simulating the horizontal distribution of horizontal wind speed. An empirical model for the vertical distribution of horizontal wind speed was presented by Wood et al. (2001). Chay et al. (2006a) then applied the modifications of Holmes and Oliver (2000) to the earlier analytical models of Oseguera and Bowles (1988). Li et al. (2012) further upgraded the earlier models of Oseguera and Bowles (1988) and Vicroy (1991) by studying the change in steady state downburst flow at the different coordinates. They added the nonlinear effects of boundary layer growth to depict the variations in the horizontal and vertical coordinates of maximum horizontal wind speed. Finally, Abd-Elaal et al. (2013a) developed a new pair of shaping functions incorporating the nonlinear effects of boundary layer growth and did not ignore the continuity equation that confirms the relationship between the vertical and horizontal speed.

To date, these models have rarely considered the changes of downburst flow with time. Holmes and Oliver (2000) introduced the first concept for depicting downburst temporal profiles by multiplying the radial velocity by a decay function. Chay et al. (2006a, 2006b) and Abd-Elaal et al. (2012) further developed the previous concept and introduced several intensity-decay functions for depicting the temporal profiles of downburst wind speed. However, the basis of these intensity-decay functions is similar; they increase and reduce the intensity of the whole flow as one unit. They utilised a one-dimensional intensity decay function for the whole downburst flow without considering the difference from one location to another in space. Whereas, through the real event life cycle, the downburst flow moves away from the impinging jet and several ring vortices travel over the flow. Such movements considerably change the profiles and the distribution of the speeds and hence require the developed intensity decay functions to include more parameters.

The importance of the investigations of temporal profiles of downburst wind speed is not only limited to dynamic analysis. Such investigations are also required for static analysis, particularly for large structures such as transmission line systems that extend for several kilometres. The distributions of wind speeds on these extended systems at any moment are sensitive to time. In the present research, the CFD simulation results are used to establish a pair of intensity-decay functions to simulate the change in the profile of both the horizontal and vertical downburst speeds with time and space. This creates 4-dimensional profiles for both of the two downburst wind speed components. The developed functions are then calibrated and verified against collections of field data.

2. Earlier intensity-decay functions

Holmes and Oliver (2000) introduced the first intensity decay function for depicting the temporal change in downburst wind speed. They multiplied their empirical model that simulated the horizontal distribution of downburst wind speed by a developed decay function Eq. (1), where t is the time measured from when the downburst is at peak intensity, and T is the time constant. Their decay function was developed to simulate the data collected by a stationary anemometer at 5.0 m height for the downburst that occurred at Andrews Air Force Base (AAFB), near Washington, D.C., U.S.A in 1983 (Fujita, 1985). However the changes in the entire temporal profiles of downburst wind speed are not synchronous to one position.

Chay et al. (2006a, 2006b) and Abd-Elaal et al. (2012) developed the previous decay functions to an intensity decay function such as Eq. (2) given in by Chay et al. (2006a). They employed the observation data in Hjelmfelt (1988) and Wilson et al. (1984), by considering a period of 5–9 min for linear intensification, then a period of 5–9 min for decay of the event.

$$\pi = e^{(-t/T)} \tag{1}$$

$$\pi = \begin{cases} t/5 & 0 \le t \le 5 \\ e^{-(t-5)/11542} & t \qquad mac; sc; 5 \end{cases} \tag{2}$$

These equations rely on the synchronisation assumption that relates the temporal change of the whole downburst wind speed profiles to the recorded temporal profile at the anemometer position, without any consideration of the profile's changes or time-shifting from one spot to others. This assumption leads to inaccurate distributions of downburst wind speed on extended structures. Fig. 1 indicates the main stages during a live downburst development as presented by earlier researchers (Fujita, 1985; Hjelmfelt, 1988). Fig. 2 presents the development of the different stages of a downburst event in a fluid dynamic model (Hangan et al., 2003; Chay et al., 2006a; Kim and Hangan, 2007; Mason et al., 2009, 2010; Vermeire et al., 2011a), while Fig. 3 shows the estimated stages for a live downburst event over time using the synchronisation assumptions in the previous decay functions. It is obvious from Fig. 3 that, the estimated speed profiles by the earlier models have steady profiles and the intensity decay functions work as an amplification factor that increases the speed intensity gradually (Fig. 3a–c) then decreases the intensity again (Fig. 3c–e).

In addition to the limitations in the previous decay functions due to adopting the synchronising assumption, they utilised unfiltered observed temporal field data for establishing their models. Several factors can significantly change the recorded data by increasing or decreasing the decay and intensity periods. For example, the parent storm translation speed that increases the downburst velocity in the front of the storm and reduces the downburst speed in the rear, can therefore give incorrect information about the decay and intensity period, and the parent storm translation speed also rapidly transforms the location of the downburst during monitoring of the event. In addition, the effect of the direction of the downburst path relative to the location of the anemometer causes another discrepancy with the observed data. Abd-Elaal et al. (2013b) investigated these factors that change the recorded data and established a new technique for measuring the age of downbursts after filtering the observed data for several downburst events. They suggested an alternative

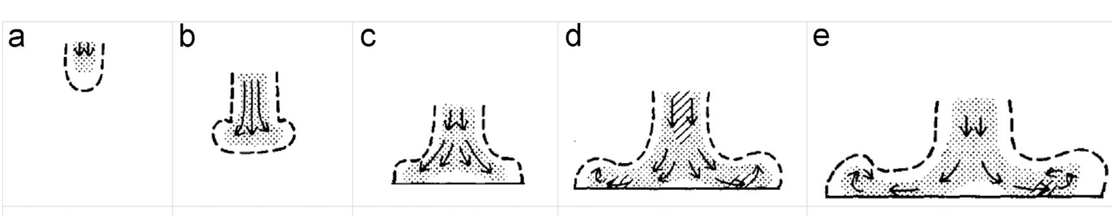

Fig. 1. Life cycle of downburst (Hjelmfelt, 1988). (a) $T-5$ min, (b) T−2 min, (c) T min, (d) T+5 min, and (e) T+10 min.