Engineering Structures 148 (2017) 509–521

Contents lists available at ScienceDirect

Engineering Structures

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

Doppler radar-derived wind field of five tornado events with application to engineering simulations

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ARTICLE INFO

Article history:
Received 20 January 2016
Revised 3 March 2017
Accepted 27 June 2017

Keywords:
Doppler radar
Tornado vortex
Velocity field
Fujita Scale

ABSTRACT

Doppler radar data corresponding to five tornado events are analyzed using the Ground-Based Velocity Track Display method and the three-dimensional velocity field of nine volumetric samples is extracted. These samples are selected to cover a range of wind speeds (between 36 m/s and 64 m/s) and vortex structures representative of EF0 to EF3 tornadoes in a first attempt to generate a tornado wind field database. Tangential velocity profiles, swirl ratios and vortex structures, i.e. single-celled or two-celled vortex, are determined for each of these volumetric samples.

Among the nine volumetric samples, two show single-celled characteristics, vortex breakdown bubble is evident in one and four demonstrate two-celled vortex characteristics. The radial profiles of the tangential velocity are in good agreement with a modified Rankine vortex model. The variation of maximum tangential velocities with height is very different when compared to the velocity variation in typical atmospheric boundary layer flows. The swirl ratios of the tornado volumetric samples are computed using the flow rate through the updrafts and the maximum circulation in the flows.

1. Introduction

The United States experiences an average of more than 1200 tornadoes per year which have resulted in around 1300 fatalities and more than $24 billion damage in the previous 15 years [1]. The damage from tornado outbreaks in 2011 exceeded $10 billion, representing the highest severe weather-related property damage in a single year since 1980 [2]. The National Institute of Standards and Technology (NIST) report [3] on the impacts of the 22 May 2011 EF5-rated Joplin, MO tornado details that a total of 553 non-residential and 7411 residential buildings were damaged to some extent with about 43 percent of the residential buildings being destroyed (i.e. damage classification of heavy/totaled or demolished). Losses from damaged buildings in this tornado, excluding damaged automobiles and other properties, totaled about $1.78 billion. While many of the affected buildings did not collapse, 84% of the total fatalities were building-related and 96% of the deaths (155 out of 161) were caused by impact–related injuries which means due to blunt force trauma.

Effectively designing tornado-resistant buildings and structures requires a detailed knowledge of the nature of the wind threat including associated flow fields, intensity, translational path and directional variability, geographical occurrence and statistics as well as debris dynamics. Characterizing the complex structure of tornado flows and simulating tornado vortices with flow characteristics similar to natural tornadoes are the main steps in achieving this long term goal. However, there are historical barriers: (i) the shortage of full-scale velocity data, (ii) the unknown relationship between actual and simulated tornadoes and (iii) the limited scale of tornado simulators.

Collecting wind field data from tornadoes in nature has been historically challenging. Technological developments of Doppler radars (e.g. introduction of Doppler On Wheels (DOW) [4]) are important recent advancements enabling full-scale tornado data collection from a safe distance. However, until now the data analysis from these measurements was mainly focused on tornadogenesis and individual events.

To ensure that experimentally or numerically simulated tornadoes have the same characteristics as field tornadoes, all the similitude requirements must be satisfied. The complexity with tornado simulations emanates from the swirl ratio (S) definition. This important controlling parameter is defined based on the geometry of a simulator and for that reason, the determination of the swirl ratio for a field tornado is difficult/subjective as inlet and outlet boundaries of a field tornado are not clearly detectable. Alternatively, Hangan and Kim [5] suggested a practical approach towards

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http://dx.doi.org/10.1016/j.engstruct.2017.06.068
0141-0296/

properly scaling tornado vortices in laboratory which was further developed and verified by Refan et al. [6].

Considering the reduced size of the simulators and therefore, their small geometric scaling ratio, modeling buildings and structures and measuring the wind-induced loads has not been practical. However, the introduction of new wind facilities, such as the WindEEE Dome at Western University, enables researchers to simulate tornado vortices in laboratory at a relatively large scale and with flow characteristics similar to real tornadoes.

It is only recently that advanced techniques have emerged at the level of field characterizations (mobile Doppler radars [4]), mathematical modeling (Ground-Based Velocity Track Display [7]) and experimental simulations (novel tornado simulators [8] and lately developed scaling practices [6]). Herein we implement some of these new techniques to characterize the flow structure and velocity field of various tornado events. First, single-Doppler radar data and the Ground-Based Velocity Track Display (GBVTD) method [7] are used to extract the three-dimensional flow field of nine volumetric samples (hereafter volumes) corresponding to five tornado events. Next, the vertical structure of the tornadoes revealed in these nine volumes are compared with simulated tornado vortices. Tornado volumes are then ranked in an increasing order of Enhanced Fujita Scale (EF-Scale) [9], determined based on radar-measured maximum tangential velocity, to avoid the subjectivity in tornado intensity ranking introduced by using damage survey findings. At the end, the swirl ratio of each volume is estimated using a new approach which is based on the flow field and then is related to the EF-Scale. This analysis has the potential to build a relationship between full-scale tornado events and physically or numerically simulated tornado-like vortices. The analyzed data will serve as the beginning of what will eventually be a database of full-scale tornado wind fields. This preliminary database can be used by researchers focusing on experimental and numerical simulations of tornadic flows with the ultimate goal of studying wind-loading effects on scaled models of buildings and structures.

2. Background

Physical [10–14] and numerical [15–18] simulations of tornado-like flows have demonstrated variations in the vortex intensity, structure and wind field, which are mainly governed by the non-dimensional parameter known as the swirl ratio (S). The swirl ratio can be defined as the ratio between the tangential velocity (V_{tan}) at the edge of the updraft hole to the mean axial velocity (V_{ax}) through the updraft opening: $S = (1/2a)V_{tan}/V_{ax}$. Where a, namely the aspect ratio, is the ratio between the inflow depth (h) and the updraft radius (r_0). The terms inflow depth (a.k.a. inflow height) and updraft hole originate from Ward-type tornado simulators and are depicted in Fig. 1.

As shown in Fig. 2, variation of the swirl ratio results in various tornado structures [19]. For very weak swirls, $S < 0.2$, the flow in the boundary layer region separates (Fig. 2a). By increasing the angular momentum, a thin laminar swirling flow forms aloft while the separated flow is forced to reattach to the surface (Fig. 2b). For moderate swirls, $0.2 < S < 0.4$, a turbulent vortex breakdown bubble forms aloft and moves towards the surface as the swirl ratio increases (Fig. 2c). At this transitional stage, the vortical flow consists of a thin core close to the ground (supercritical zone) and a turbulent two-celled flow aloft (subcritical zone). By further increasing the swirl ratio, a downdraft develops along the centerline and eventually the breakdown bubble touches the surface at $S \approx 0.45$ (Fig. 2d). For $0.8 < S < 1.4$, a two-celled vortex with a central downdraft impinging on the ground is observed (Fig. 2e). The tornado vortex can split into two or more cells if the swirl increases further (Fig. 2f). As explained by Hall [20,21], a key feature of quasi-cylindrical vortices is to develop an adverse axial pressure gradient which is related to the radial expansion of the turbulent core aloft. As a result, the updraft decelerates at the centerline and maximum vertical velocities relocate to an annular ring surrounding the vortex breakdown bubble. The presence of vortex breakdowns in actual tornadoes has been confirmed by Pauley and Snow [22] and Lugt [23]. Note that the swirl ratio values and ranges provided above correspond to measurements performed in a Ward-type tornado simulator [24].

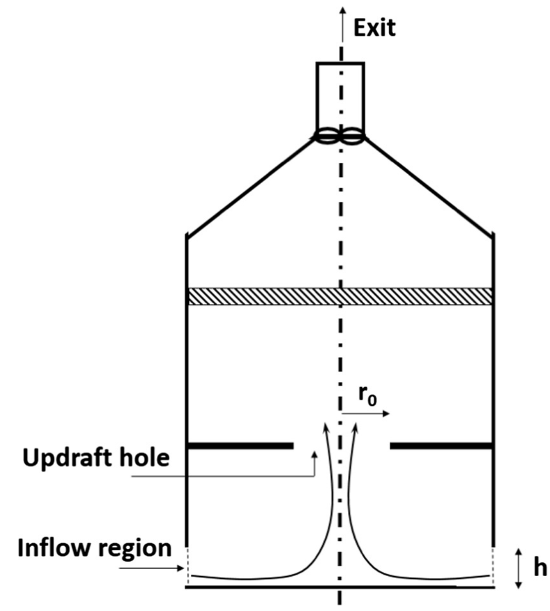

Fig. 1. Schematic drawing of a typical Ward-type tornado simualtor.

Single- and dual-Doppler radar data from over 200 individual tornadoes have been collected using proximate mobile Doppler On Wheels (DOW) radars [4,25] during field projects such as Verification of the Origins of Rotation in Tornadoes Experiment 1 (VORTEX1: 1994–1995), Radar Observations of Tornadoes And Thunderstorms Experiment (ROTATE: 1996–2001; 2003–08; 2012–13) and VORTEX2 (2009–2010). The first three-dimensional maps of a tornado vortex inner and outer core flow with fine temporal and spatial resolution were obtained using the prototype DOW mobile radar in VORTEX1 [26]. These tornado wind maps allowed for recording the horizontal and vertical structure of the vortex and its evolution [27–29]. ROTATE [30,31] collected single- and dual-Doppler radar data from more than 140 different tornadic events that enabled the study of tornadogenesis [32], tornado structure [33–37] and the relationship between tornadic winds, debris, and damage [38–40].

ROTATE (2012–13) is the most recent field study of tornadoes focused on the low-level winds and therefore of great interest for the wind engineering community. Using data collected during this field project, Kosiba and Wurman [41], for the first time, documented the fine-scale three-dimensional structure of the surface layer in a tornado.

The Ground-Based Velocity Track Display (GBVTD) technique was developed by Lee et al. [7] to resolve the wind structure of a tropical cyclone using single-Doppler radar data. The method was then extended by Lee and Wurman [35] to retrieve three-dimensional structure of tornadoes. Since then, the GBVTD method has been used by many researchers [36,37,41–46] to extract the wind field of tornadoes from single-Doppler radar measured data.

Lately, Nolan [47] performed a thorough review on the accuracy of the GBVTD method in retrieving velocity fields from single-Doppler radar data. He concluded that vertical velocities obtained