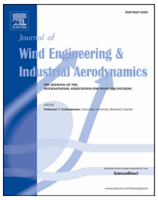
Journal of Wind Engineering & Industrial Aerodynamics 177 (2018) 306–326

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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



Numerical study of the structure and dynamics of a tornado at the sub-critical vortex breakdown stage

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ARTICLE INFO

Keywords:
Tornado
LES
Numerical simulation
Breakdown
Reynolds averaged force balance
TKE budget
Spectrum

ABSTRACT

A tornado at the sub-critical vortex breakdown was studied in detail using large eddy simulations. The averaged flow fields and the fluctuations were examined. Correlations of the fluctuating parameters were also studied, and a special turbulence structure was found. To clarify this turbulence structure, the Reynolds averaged force balances in two directions were studied, in which the sub-terms of the turbulence forces were paid more attention. The turbulence kinetic energy budget was examined to understand the balance between turbulence production, transportation, dissipation, and advection, among others. The time histories of wind velocities at some representative points were recorded, and three types of motions were then observed. The strength of these motions was furthered examined through spectrum analysis to study the change in them at different heights. Finally, the flow field visualization was performed to reveal the mechanism underlying these motions and explain some interesting phenomena found in the present study.

1. Introduction

In recent years, many studies have been conducted to examine flow structures in tornados, most of which focus on time-averaged flow fields and the fluctuations. Some important findings have been obtained, such as the strong jet flow close to the ground, the low pressure in the core, and the Ekman-like spiral, etc. The most important parameter determining the flow structure was found and named as swirl ratio. By increasing this parameter, the tornado will experience several stages, i.e., single-celled vortex, vortex breakdown, vortex touchdown, two-celled vortex, and multi-celled vortex, as shown in Fig. 1. For the single celled vortex, the core extends upward from the surface to higher levels and spreads slightly. At the vortex breakdown stage, the flow changes from a tight, laminar vortex to a broader, turbulent state. The laminar flow with a very narrow core in the lower portion moves upward until it suddenly expands into a recirculation bubble. For the two-celled vortex, the inner core flow moves downward but the flow surrounding the core of tornado moves upward. And at the multi-celled vortex stage, a family of several secondary vortices rotating around the main vortex is evident.

The different types of tornado like vortices have been reproduced successfully by various types of tornado simulators. The first tornado simulator was developed by Ward (1972) and then applied by many researchers, i.e., Church (1977, 1979), Monji (1985), Diamond and Wilkins (1984), Mishra et al. (2008), and Matsui and Tamura (2009), etc. For this type of tornado simulator, the swirling of the fluid is provided by the rotating screen or guide vanes mounted on the ground. In the last decade, a new tornado simulator was developed at Iowa State University are then applied by Tari et al. (2010), Kikitsu et al. (2012), Cao et al. (2015), and Wang et al. (2016), etc. For this type of tornado simulator, the swirling of the fluid is provided by the guide vane mounted on the top of simulator and the circulation of the fluid in tornadoes could also be modelled. Most recently, Refan et al. (2014) developed a tornado simulator in WindEEE. In this simulator, the swirling of the fluid was provided the through the fans whose direction could be controlled. Fig. 2 summarizes the reproduced different types of tornadoes in different types of tornado simulators. In the studies listed in Fig. 2, the definition of the swirl ratio is same, $S = r_o\Gamma/2Qh$, where Γ is the circulation magnitude, r_o the radius of the updraft hole and Q represents the flow rate. Generally speaking, based on the definition of swirl ratio adopted, the single celled vortex occurs in the range of $0 < S < 0.4$, and the two celled or multi celled vortex occurs in the range of $S > 0.7$. In the range of $0.4 \leq S \leq 0.7$, the vortex is in a transient stage where the vortex breakdown appears. Focusing on the vortex breakdown, some interesting features have been found. In the following, a brief summary of the properties of the

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https://doi.org/10.1016/j.jweia.2018.04.009
Received 2 September 2017; Received in revised form 28 December 2017; Accepted 9 April 2018

Nomenclature

A	aspect ratio
A	advection budget of TKE
A_{ri}	radial advection term
A_{zi}	vertical advection term
C_{r}	centrifugal force term
C_s	Smagorinsky constant
D	distance to the closest wall
D	dissipation of TKE
D_{i}	diffusion term
h	height of the inlet layer [m]
k	turbulence kinetic energy [$\mathrm{m^2 s^{-2}}$]
$\mathrm{L_s}$	mixing length for subgrid-scales[m]
$\tilde{p}$	filtered pressure[$\mathrm{N\ m^{-2}}$]
P	production of TKE
P_{r}	radial pressure gradient term
$\mathrm{P_r}$	pressure diffusion of TKE
P_{z}	axial pressure gradient term
Q	flow rate [$\mathrm{m^3\ s^{-1}}$]
r_0	radius of the updraft hole[m]
r_{c}	Radius at which V_{c} occurs [m]
Re	Reynolds number
r_{s}	radius of the convergent region[m]
r_t	radius of the exhaust outlet[m]
$\tilde{S}_{ij}$	rate-of-strain tensor [$\mathrm{s^{-1}}$]
T	turbulence transportation of TKE
T_{i}	turbulent force term
$\tilde{u}_i$	filtered velocities [$\mathrm{ms^{-1}}$]
(U,V,W)	Mean radial, tangential and vertical velocities [$\mathrm{m\ s^{-1}}$]
$u_{\mathrm{i}}u_{\mathrm{j}}$	Reynolds stresses [$\mathrm{m^2\ s^{-2}}$]
U_{rs}	radial velocities at $r = r_{\mathrm{s}}$[$\mathrm{m\ s^{-1}}$]
u_τ	friction velocity[$\mathrm{m\ s^{-1}}$]
V_{c}	maximum mean tangential velocity at the cyclostrophic balance region[$\mathrm{m\ s^{-1}}$]
V_{rs}	tangential velocity at $r = r_{\mathrm{s}}$[$\mathrm{m\ s^{-1}}$]
W_0	velocity at the outlet[$\mathrm{m\ s^{-1}}$]
(x, y, z)	Cartesian coordinates[m]

Greek symbols

δ_{ij}	Kronecker delta
Γ_∞	free-stream circulation at the outer edge of the convergence region[$\mathrm{m^3\ s^{-1}}$]
θ	inflow angle [°]
κ	von Kármán constant
μ	Viscosity [Pa·s]
μ_{t}	SGS turbulent viscosity [Pa·s]
ρ	density [$\mathrm{kg\ m^{-3}}$]
τ_{ij}	SGS stress [$\mathrm{N\ m^{-2}}$]

Abbreviations

DPM	Discrete Phase Method
LES	large-eddy simulation
MEM	Maximum Entropy Method
r.m.s	root mean square
SGS	subgrid-scale
SIMPLE	semi-implicit pressure linked equations
TKE	turbulence kinetic energy

tornado-like vortex at breakdown stage will be provided.

The vortex breakdown (Harvey, 1962; Benjamin, 1962; Lugt, 1989) is considered to be an axisymmetric analog to the hydraulic jump phenomenon observed in channel flows. As S is increased, the altitude of the vortex breakdown decreases; until the breakdown is just above the surface (Church, 1979; Church and Snow, 1977). This state has been referred to as a "drowned vortex jump'' (DVJ; Maxworthy, 1973) and is generally associated with having the highest near surface azimuthal wind velocities. When S is further increased, the vortex breakdown reaches the surface. The decrease of the altitude of the vortex bubble as increasing the swirl ratio is illustrated in Fig. 3.

As observed in experiments by Refan et al. (2014), at the vortex breakdown stage the flow is highly unstable as it consists of three distinct dynamic regions: turbulent sub-critical region aloft followed by the breakdown bubble in the middle and the narrow super-critical core close to the ground. Following the discussion by Refan and Hangan (2016) at the stage where the vortex breakdown reaches the surface is considered to be "subcritical". In that study they also found that the development of the free stagnation point towards the surface continues until it touches the ground at around $S = 0.57$. Pauley (2010) performed pressure measurements of the vortex axis using a Ward-type tornado simulator, and the static pressure measured along the vortex axis increased with the height downstream of the vortex breakdown flow. In that study, force balance analysis in the axial direction was also performed, and it was concluded that turbulent stresses can play an important role in the axial momentum balance. From the experiment by Tari et al. (2010), we can see at the sub-critical vortex breakdown stage ($S = 0.68$), the fluctuations of the velocity are very high. Due to the instabilities associated with the vortex break-down bubble and the transition from laminar to turbulent flow, one can expect considerable variations in the vortex characteristics and structures.

Numerical simulation is another important way to study the transition stage–vortex breakdown. Using complete information for the flow fields in the tornado-like vortex, more details of the flow can be provided. Refan and Hangan (2016) numerically studied tornadic vortices and concluded that vortex breakdown involves a complex interaction between two competing tendencies. The first is the production of an axial up-draught as an extension of the convergent boundary layer, and the second is the decay of the tangential velocity with height. Lewellen D.C. and Lewellen W.S. (2007) examined the near surface intensification of tornado-like vortices and showed that the vortex breakdown stage represents a sharp transition from states with strong upward axial flows to those with significantly large core radii, reduced axial velocities, and increased turbulence levels. In systematic research of examining four typical tornados by Liu and Ishihara (2015), the turbulence characteristics and force balances in the radial as well as vertical directions were evaluated, in which an extraordinarily high turbulence was found at the stage of sub-critical vortex breakdown ($S = 0.6$). It is this case that will be examined in detailed in the present study as illustrated by red dashed line in Fig. 2.

As found in the studies summarized above, at the sub-critical vortex breakdown stage, the turbulence in the fluid is very high. However, up to now no detailed explanation of this phenomenon was provided due to the insufficient recorded data. But the clarification of the high turbulence is a very important issue for wind resistant design when a structure is exposed to a tornado-like vortex sub-critical vortex breakdown stage.

In this study, the mean and fluctuating flow fields, the force balance and the dynamics of the tornado at the vortex breakdown stage will be examined in detail using three-dimensional large eddy simulations, and the reasons for the occurrence of high turbulence at this stage will be revealed in a step-by-step manner. The correlation of the fluctuating parameters and the balance of turbulence kinetic energy (TKE) for sub-critical vortex breakdown stage will be examined as well, which is important for understanding the structure of the turbulence. Spectrum analysis of the wind speeds for sub-critical vortex breakdown stage will be conducted, which is important for understanding the dynamic