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Study of the effects of translation and roughness on tornado-like vortices by large-eddy simulations

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ABSTRACT

The numerical simulation by LES turbulent model for translating tornadoes and those over roughness was carried out in a Ward type simulator. The tornado translation was modeled by providing a relative motion on the ground and the roughness was simulated through adding a momentum source in the Navier–Stokes equation. The effects of translation and roughness on the flow fields of three typical tornado-like vortices, i.e., vortex breakdown, vortex touching down and multi-vortex, were investigated and the detailed velocity distributions, Reynolds stresses and the pressure on the ground were examined. The similarity of the flow fields after the introduction of translation and ground roughness was also studied. It was found that, at the high elevation, V_c and r_c shows the same trend versus the external swirl ratio for stationary and translating tornadoes. However, if the ground is rough, the core radius at high elevation changes greatly. The ground roughness will expand the size of the core. But for the very small swirl ratio cases, the ground roughness shows the effect reducing the core size. The explanation for the evolution of the flow fields due to translation and ground roughness is provided.

1. Introduction

Researchers have conducted intensive studies concerning flow structures, dynamics and similarity of tornado-like vortices. Consequently, a large number of significant findings have been obtained, such as dominant parameters determining flow structure (see, e.g., Ward (1972), Rotunno (1977), Church et al. (1979) and Kuai et al. (2008)), organized swirl motion in tornadoes (see, e.g., Monji (1985), and Ishihara and Liu (2014)) and similarity between simulated tornadoes and those in nature (see, e.g., Hangan and Kim (2008) and Liu and Ishihara (2015a)). The majority of these studies focus on the stationary tornadoes on smooth ground. However, tornadoes in nature are frequently observed with a translation speed ranging from 10 m/s to 30 m/s, such as the tornado took place in Spencer, South Dakota, the US in 1998, which was observed by Wurman and Alexander (2005). Furthermore, tornados can also occur in urban area, such as the tornado occurred in Joplin, Missouri, the US in 2011, which was reported by Doswell et al. (2012).

By adding a movable ground plate in Ward type simulator, translation effects were studied by Diamond and Wilkins (1984) experimentally and secondary vortices were found to be generated by the translation. Most recently, through large eddy simulation, the effect of tornado translation was investigated by Natarajan and Hangan (2012) in a larger range of swirl ratio. In addition, the method simulating tornado translation is same as that in the study performed by Diamond and Wilkins (1984) who found that the effect was not uniform across external swirl ratios. However, there was no quantitative explanation regarding translation effects on tornado configuration.

In order to study how surface roughness has an influence on velocities, pressure and core radius, a large number of researches have been performed. However, researchers are not in complete agreement on how the roughness affects them. As found by Diamond and Wilkins (1984) and Zhang and Sarkar (2008), the vortex diameter decreases with the introduction of ground roughness, while the results from Dessens (1972), Leslie (1977), Monji and Wang (1989) and Natarajan and Hangan (2012) demonstrate that the effect of increasing surface roughness was to enlarge the vortex core. Besides, the shrink mechanism or tornado size expansion due to roughness must be clarified.

By adopting LES model, flow fields of tornado-like vortices after the introduction of translation and roughness are investigated in this study, so as to shed light on the effects of these factors. In Section 2, the details of the model simulating tornado translation and roughness will be introduced, including dimension, grid distribution, boundary conditions and definitions of swirl ratio.

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Nomenclature

$a_{\tilde{u}}$	frontal area density of roughness
C_d	drag coefficient of roughness
h_R	height of roughness
$h_{v\ max}$	height at which V_{max} occurs
P_{min}	minimum pressure drop
r_0	radius of updraft hole of simulator
r_c	radius at which V_c occurs
$r_{v\ max}$	radius at which V_{max} occurs
S_c	local corner swirl ratio
S_E	external swirl ratio
U	mean radial velocity
U_{min}	minimum radial velocity
u'	r.m.s of fluctuating radial velocity
V	mean tangential velocity
V_c	maximum tangential velocity in the cyclostrophic balance region
V_{max}	maximum tangential velocity
v_T	translation speed of tornado
v'	r.m.s of fluctuating tangential velocity
W	mean vertical velocity
W_0	upward velocity at outlet of simulator
W_{max}	maximum vertical velocity
w'	r.m.s of fluctuating vertical velocity

Section 3 provides a general view of the effects from tornado translation and ground roughness. In Section 4 and Section 5, the translation and roughness effects on the flow fields of tornado-like vortices and their mechanisms will be discussed. The detailed information of the mean flow fields and the Reynolds Stresses will be also provided.

2. Numerical model

The governing equations will be introduced in Section 2.1. Section 2.2 will provide the detailed information of the configurations for the numerical tornado simulator. Boundary conditions and the solution schemes will be presented in Sections 2.3 and 2.4. The methods simulating tornado translation and surface roughness will be introduced in Sections 2.5 and 2.6. Section 2.7 gives the definitions of swirl ratio.

2.1. Governing equations

As momentum and mass are mainly transported by large eddies, large eddy simulation (LES) is employed to simulate the tornado-like vortex in consideration of the current computing capability. In LES, large eddies are computed directly, while the influence of eddies smaller than grid spacing are modeled. Although LES is computationally expensive, it can provide detailed and accurate information. In addition, standard Smagorinsky–Lilly model is adopted to calculate subgrid-scale (SGS) stresses.

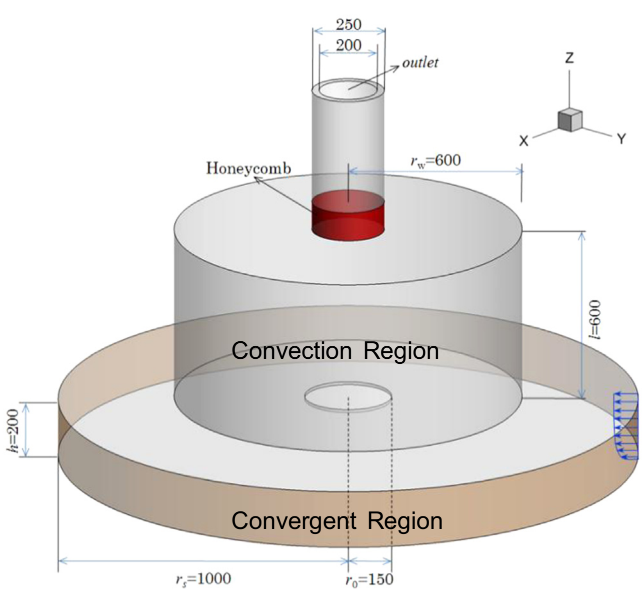

Fig. 1. Geometry of the model. Red color shows the location of honeycomb. Arrows indicate the direction of flow at the inlet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

By filtering time-dependent Navier–Stokes equations in Cartesian coordinates (x, y, z), governing equations are obtained and expressed in the form of tensor as follows:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\frac{\partial \tilde{u}_i}{\partial t} + \rho\frac{\partial \tilde{u}_i\tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\mu\frac{\partial \tilde{u}_i}{\partial x_j}\right) - \frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

of which $\tilde{u}_i$ and $\tilde{p}$ are respectively filtered velocities and pressure, μ is viscosity, ρ is density, τ_{ij} is SGS stress and modeled as follows:

$$\tau_{ij} = -2\mu_t\tilde{S}_{ij} + \frac{1}{3}\tau_{kk}\delta_{ij}; \quad \tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) \tag{3}$$

where μ_t denotes SGS turbulent viscosity and $\tilde{S}_{ij}$ is the rate-of-strain tensor for the resolved scale, δ_{ij} is the Kronecker delta. Smagorinsky–Lilly model is employed for the SGS turbulent viscosity:

$$\mu_t = \rho L_s^2|\tilde{S}| = \rho L_s^2\sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}}, \quad L_s = \min\left(\kappa d, C_s V^{\frac{1}{3}}\right) \tag{4}$$

in which L_s denotes the mixing length for subgrid-scales, κ is the von Kármán constant, 0.42, d is the distance to the closest wall and V is the volume of a computational cell. C_s is Smagorinsky constant. In this study, C_s is determined as 0.032 based on the study performed by Ishihara and Liu (2014) and (2015a). In those studies, the flow fields of tornado like vortices in simulation have shown good agreements with experiments. The numerical simulators in the present study, the study by Ishihara and Liu (2014), (2015a), and (2015b) are same. Therefore, we would like to follow the previous studies and use the same C_s value. Following comparison with the observation data shows good agreement, see Fig. 19, which also verify C_s value used in the present study.

Table 1
Physical parameters of numerical tornado simulator.

Height of the inlet layer (h)	200 mm
Radius of the updraft hole (r_0)	150 mm
Internal aspect ratio ($a = h/r_0$)	1.33
Radius of the exhaust outlet (r_t)	100 mm
Radius of the convergence region (r_s)	1000 mm
Velocity at the outlet (W_0)	9.55 m/s^{-}
Total outflow rate ($Q = \pi r_t^2 W_0$)	0.3 m^3/s
Reynolds number ($Re = 2r_0W_0/\nu$)	1.60×10^5