Wind and Structures, *Vol. 26, No. 3 (2018) 179-190*
DOI: https://doi.org/10.12989/was.2018.26.3.179

Laboratory investigation of the effects of translation on the near-ground tornado flow field

Alireza Razavi[a] and Partha P. Sarkar*

Department of Aerospace Engineering, Iowa State University, Ames, IA 50011, USA

(Received October 26, 2017, Revised December 29, 2017, Accepted January 21, 2018)

Abstract. Translation of tornadoes is an important feature in replicating the near-ground tornado flow field which has been simulated in previous studies based on Ward-type tornado simulators using relative motion of the ground plane. In this laboratory investigation, effects of translation on the near-ground tornado flow field were studied using the ISU Tornado Simulator that can physically translate over a ground plane. Two translation speeds, 0.15 m/s and 0.50 m/s, that scale up to those corresponding to slowly-moving tornadoes in the field were selected for this study. Compared with the flow field of a stationary tornado, the simulated tornado with translation had an influence on the spatial distribution and magnitude of the horizontal velocities, early reversal of the radial inflow, and expansion of the core radius. Maximum horizontal velocities were observed to occur behind the center of the translating tornado and on the right side of its mean path. An increase in translation speed, resulted in reduction of maximum horizontal velocities at all heights. Comparison of the results with previous studies that used relative motion of the ground plane for simulating translating tornadoes, showed that translation has similar effects on the flow field at smaller radial distances (~2 core radius), but different effects at larger radial distances (~4 core radius). Further, it showed that the effect of translation on velocity profiles is noticeable at and above an elevation of ~0.6 core radius, unlike those in studies based on the relative motion of the ground plane.

Keywords: tornado simulation; ISU tornado simulator; translating tornado; Tornado-like vortex; tornado wind

1. Introduction

Based on three-year average (2014-2016) statistics, about 1000 tornadoes touch down annually in the US causing 29 fatalities(http://www.spc.noaa.gov/climo/online/monthly/newm.html) and immense property loss. This highlights the vulnerability of lives and infrastructure to tornadoes and calls for investigation of significant parameters that influence the near-ground wind field in tornadoes. Since the pioneering work of Ward (1972), many studies have been done on tornado flow field (Ward 1972, Dessens Jr. 1972, Davies-Jones 1973, Jischke and Parang 1974, Leslie 1977, Rotunno 1977, Church *et al.* 1979, Diamond and Wilkins 1984, Lewellen *et al.* 1997, Haan *et al.* 2008, Hashemi Tari *et al.* 2010, Natarajan and Hangan 2012, Razavi and Sarkar 2016, Refan and Hangan 2016, Liu and Ishihara 2016). Initially, these studies focused on understanding of the wind-flow structure of stationary tornadoes and important parameters that influences it, i.e., swirl ratio, ratio of angular to radial momentum, radial Reynolds number and aspect ratio, ratio of a characteristic height to a characteristic radius (Ward 1972, Davies-Jones 1973, Jischke and Parang 1974, Church *et al.* 1979), whereas the later and more recent studies included the roles of tornado translation and ground roughness (Dessens 1972, Leslie 1977, Diamond and Wilkins 1984, Lewellen *et al.* 1997, Lewellen *et al.* 1997, Natarajan and Hangan 2012, Liu and Ishihara 2016) on the tornado-flow structure. The Ward-type simulator could not simulate translating tornadoes, so relative motion of the ground plane was used in simulation of translating tornadoes. Diamond and Wilkins (1984) simulated a translating tornado with relative motion of the ground plane in a laboratory apparatus, where they observed core expansion as a result of local increase in swirl ratio. Lewellen *et al.* (1997) repeated the same procedure except using a numerical simulation and observed a slight increase in the mean velocities and a greater increase of the fluctuating velocities at certain locations. The maximum increase in the mean and fluctuating components of the total velocity occurred inside the tornado core at lower elevations near the ground. It was also observed that the tornado center (center of rotation) at low elevations close to the ground plane, lags behind the tornado center at higher elevations and occurs on the right side of the tornado's mean path. Natarajan and Hangan (2012) used a numerical model and implemented the same method of moving ground plane to study the effects of tornado translation on flow field of stationary cases, while considering different swirl ratios. They concluded that the maximum mean tangential velocity of high-swirl tornadoes increases, while it decreases in low-swirl tornadoes as a result of translation. Most recently, Liu and Ishihara (2016) used a numerical model to investigate effects of tornado translation on flow field of stationary tornadoes by translation of the ground plane and concluded that, while effects of translation on core radius and tangential velocity is negligible, its effect on vertical velocity is significant.

They also stated that their conclusions based on using

*Corresponding author, Professor
E-mail: ppsarkar@iastate.edu
[a] Graduate Research Assistant

ISSN: 1226-6116 (Print), 1598-6225 (Online)

the relative motion approach is only valid close to the ground plane.

In the current study, the ISU Tornado Simulator that can simulate translating tornadoes by horizontal translation of the simulator hanging above the ground plane was used to investigate effects of horizontal translation speed of a tornado on its near-ground flow field. These flow fields of simulated tornadoes with different translation speeds were then compared to one another and that of the parent stationary tornado. This study also seeks to find the degree of agreement among results from different approaches in studying translating tornadoes, i.e., studies based on relative motion of ground plane and translation of simulator.

2. Methodology

In this section, mechanism of tornado simulation using the ISU Tornado Simulator is explained, parameters that control tornado structure are defined, characteristics of instruments used are clarified, grid points for measurement are tabulated and procedure to measure velocity time histories is described.

2.1 ISU Tornado Simulator

In the ISU Tornado Simulator (see Fig. 1), a vertically suspended fan at the center of the simulator sucks the air upward to produce an updraft that passes through a series of screens and a honeycomb at the fan inlet to remove the fan’s influence on the upstream flow. The airflow downstream of the fan is then guided into an annular duct at the top of the simulator, where it flows radially outward and passes through a series of equally spaced vanes, located around the outer periphery of the annular duct.

These control vanes are in the form of thin plates that rotate about a hinge to add angular momentum to the flow. The swirling flow is then guided through a vertical duct that is circular in shape along the outer periphery of the simulator to simulate a downdraft that is released close to the ground plane. This swirling flow that exits the outer duct is sucked towards the center of the simulator, where there is a pressure deficit, and becomes part of the inflow in the vicinity of the ground plane before becoming part of the rotating updraft in the central part of the simulator. The relatively slow swirling flow that exits the outer duct gains angular momentum as it flows toward the center of the simulator as a result of reduction in the radius of rotation and therefore sees an increase in tangential velocity. The horizontal translation of the simulator is enabled with the help of a 5-ton crane from which the simulator is suspended above the ground plane. Vane angles can be manually adjusted from 0 to 90 degrees with respect to radial direction, the inlet height or space between the outer duct and the ground plane can be adjusted by moving the ground plane up or down, the translation speed of the simulator can be varied up to 0.61 m/s and the maximum flow rate of 23 m^3/s can be practically achieved. Further details of this simulator can be found in Haan *et al.* (2008).

2.2 Tornado simulation

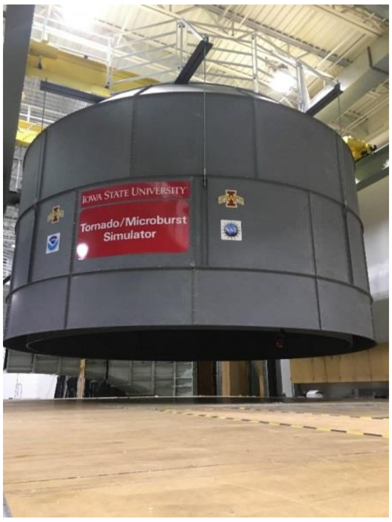
To study effects of translation on tornado flow field, controlling parameters of the ISU Tornado Simulator were adjusted to the values given in Table 1. Important non-dimensional parameters (Lewellen 1962, Church *et al.* 1979) defining the structure of the simulated tornado, including the swirl ratio, the radial Reynolds number, and the aspect ratio, were calculated based on Eqs. (1)-(4)

$$S_c = \frac{r_c \Gamma}{2Q'h} = \frac{r_c(2\pi r_c V_{\theta.c})}{2Q} = \frac{\pi r_c^2 V_{\theta.c}}{Q} = 0.25 \tag{1}$$

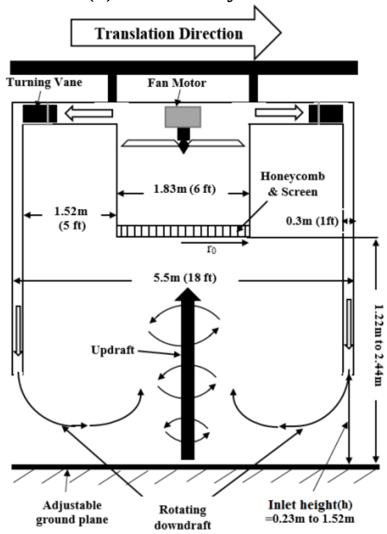
$$S_{vane} = \frac{\tan\theta}{2a} = 0.86 \tag{1}$$

$$a = \frac{h}{r_0} = 0.84 \tag{3}$$

$$Re_r = \frac{Q'}{2\pi\nu} = 1.68\times10^5 \tag{4}$$



(a) Laboratory view



(b) Schematic illustration

Fig. 1 ISU Tornado Simulator

Table 1 Control parameters of the ISU Tornado Simulator

Control parameter	Value
Vane angle (deg)	55
Flow rate (m^3/s)	12.03
Inlet height (m)	0.76

Table 2 Dimension of the grid points

Dimension	Values
r(m) (Stationary tornado)	0, 0.13, 0.23, 0.25, 0.28, 0.32, 0.38, 0.51, 0.64, 0.89, 1.14, 1.4
y(m) (Translating tornado)	0, ±0.13, ±0.25, ±0.38, -0.51, ±0.64, ±0.89, ±1.14
z(m)	0.013, 0.019, 0.025, 0.051,0.1, 0.18, 0.28

where $V_{\theta.c}$ is maximum mean tangential velocity in the flow field, r_c is core radius at which $V_{\theta.c}$ occurs, S_c is swirl ratio at the r_c, Γ is circulation defined at the r_c, Q' is volume flow rate per unit inlet height, h is inlet height, Q is volume flow rate, S_{vane} is swirl ratio at the radial location of the vanes, θ is vane angle relative to the radial direction, a is aspect ratio, r_0 is the fan radius, Re_r is radial Reynolds number, and ν is kinematic viscosity of air, taken as 1.5×10^{-5} m^2/s. S_c is an alternative definition of swirl ratio, first defined by Haan *et al.* (2008) to relate swirl ratio to characteristic velocity and length, $V_{\theta.c}$ and r_c , in tornado flow field. The flow fields of a stationary tornado and two translating tornadoes with translation speeds of 0.15 m/s and 0.5 m/s were studied and presented in this paper.

2.3 Instrument

For measurement of velocity components in the flow field of the simulated tornado, a pressure-based probe known as the Omni-probe (DANTEC 18-hole) was used. Measurement accuracy of this probe is ±2% in velocity magnitude and ±1.5^o in velocity angle (Haan *et al.* 2008).

This probe can measure velocities within a cone angle of ±165 degrees about its axis and hence, was the only choice in this study of a velocity field that is highly three dimensional. Since total velocity at the center of the translating tornadoes was in the order of 1-2 m/s, measurements of the Omni-probe were compared side-by-side in a straight-line Atmospheric Boundary Layer (ABL) wind tunnel at Iowa State University, with another pressure-based probe known as the Cobra-probe (TFI), that is considered accurate in capturing velocities as low as 2 m/s.

This comparison showed that the Omni-probe can accurately measure mean velocities as low as 2 m/s. Narrow cone angle of measurement domain of the Cobra-probe, which is ±45 degrees about its axis, prevents it to detect flow field of a translating tornado as it passes over it, because of flow reversal and high turbulence, and hence makes it inappropriate for the current study. Furthermore, Particle Image Velocimetry (PIV) was impractical, because of the large domain of this experiment that demands large seed particles for the available pixel resolution (Haan *et al.* 2008) and requires a high-resolution camera.

2.4 Experiemtal grid

The Omni-probe was located at several locations in radial (r) and vertical directions (z) for stationary tornado, and in y and z directions for translating tornadoes (Table 2).

The grid for the measurement points was selected such that the grid is relatively fine within the tornado core near the tornado center and coarse outside the tornado core or far from the tornado center. This is chosen based on the demand for measurement resolution, knowing that there is larger velocity fluctuations and velocity gradients within the core region than those outside the core. For the stationary tornado, r=0 corresponds to the center of tornado. The center of the stationary tornado was found by finding the center of symmetry of the ground surface pressure, using 30 pressure taps that were spaced 0.05 m apart. For translating tornadoes, the x-axis was taken in translation direction, the y-axis was normal to the translation direction with y=0 located at the mean center of rotation of the stationary tornado, and the z-axis was the height above the ground plane with z=0 located on the ground plane. Grid points in the z direction were similar for both stationary and translating tornadoes.

2.5 Procedure

It was assumed that flow field of the stationary tornado was axisymmetric. Since the structure of the simulator and boundary conditions were axisymmetric, velocity measurement was done in one radial direction. Velocity components were measured and averaged in time for a relatively long duration (180s). For translating tornadoes, velocity time histories were sampled at each spatial point (Table 2) for 40s and 10s which are required times for the tornado to translate over the entire length of the ground plane corresponding to translation speed of 0.15 m/s and 0.50m/s, respectively. For translating tornadoes, three data runs were sampled at each spatial point for ensemble averaging which is reported in this study. A sampling rate of 200 Hz was used for all measurements. All the measurements were done on a vertical plane with constant position in x-direction. To observe the mean flow field of the tornado along the x-direction, time domain was mapped into the space domain, knowing the time steps and the

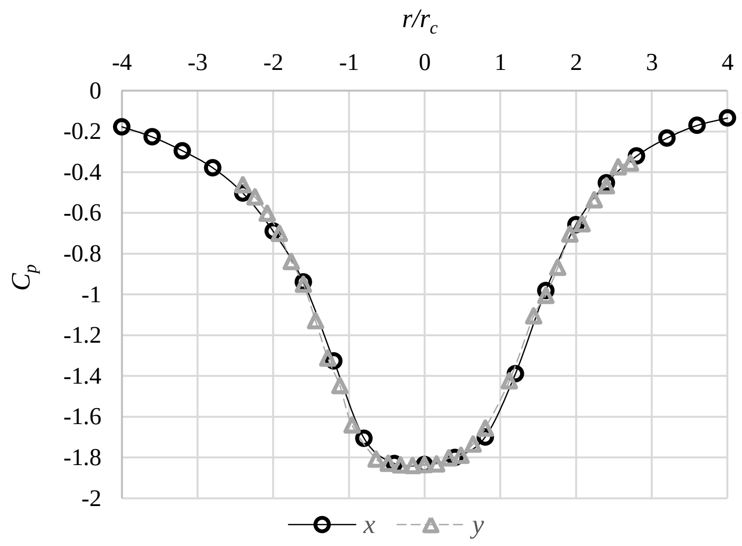


Fig. 2 Normalized ground surface pressure distribution of the stationary tornado along the translation direction (x) and normal to the translation direction (y), both passing the center of the stationary tornado

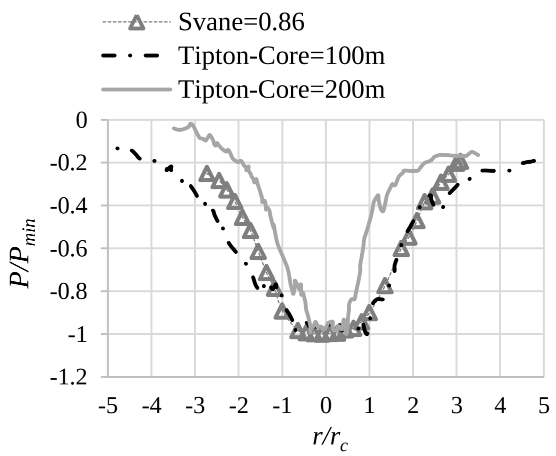


Fig. 3 Comparison of mean ground pressure between experimental and field measurements

translation speeds.

3. Results and discussion

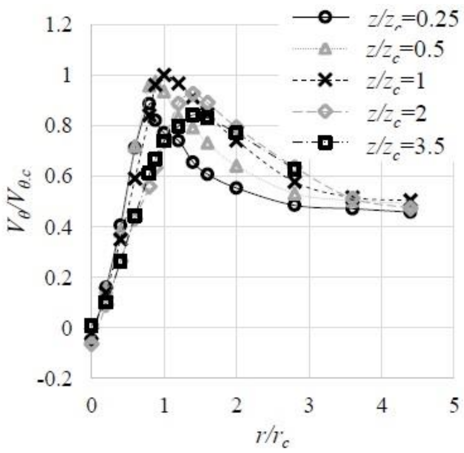
This section presents profiles of velocity components for stationary and translating tornadoes and their comparisons, comparison of velocity profiles of the simulated translating tornadoes from two approaches of relative motion of the ground plane and translation of the simulator, and contours of velocity for a translating tornado on several horizontal planes at different elevations from the ground that are usually relevant to engineering applications.

3.1 Stationary tornado

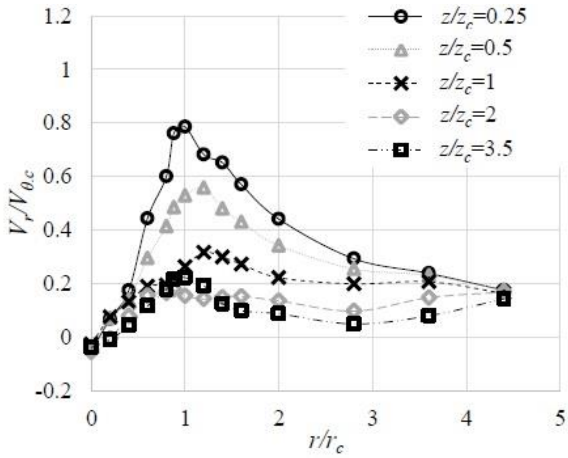
Radial distribution of ground surface pressure and radial profiles of horizontal velocity components (tangential and radial) at different heights for the stationary tornado are shown in Figs. 2 through 4. Velocities were normalized with $V_{\theta.c}$=10.8 m/s and radial distances and elevations were normalized with r_c=0.32 m and z_c=0.05 m (elevation at which $V_{\theta.c}$ occurs), respectively. Ground surface mean pressure coefficients were calculated based on Eq. (5)

$$C_p = \frac{\Delta P}{0.5\rho V_{\theta.c}^2} \tag{5}$$

where C_p is mean pressure coefficient, ΔP is pressure difference relative to far-field atmospheric pressure in the laboratory, and ρ is air density taken as 1.225 kg/m^3 based on laboratory conditions. The far-field atmospheric pressure was measured by the reference port of the pressure scanner placed underneath the ground plane of the tornado simulator at an adequate distance from it and its magnitude usually



(a) Mean *tangential* velocity



(b) Mean *radial* velocity

Fig. 4 Normalized radial profiles of mean velocity components for a stationary tornado

varied between 98.4 kPa to 101.3 kPa.

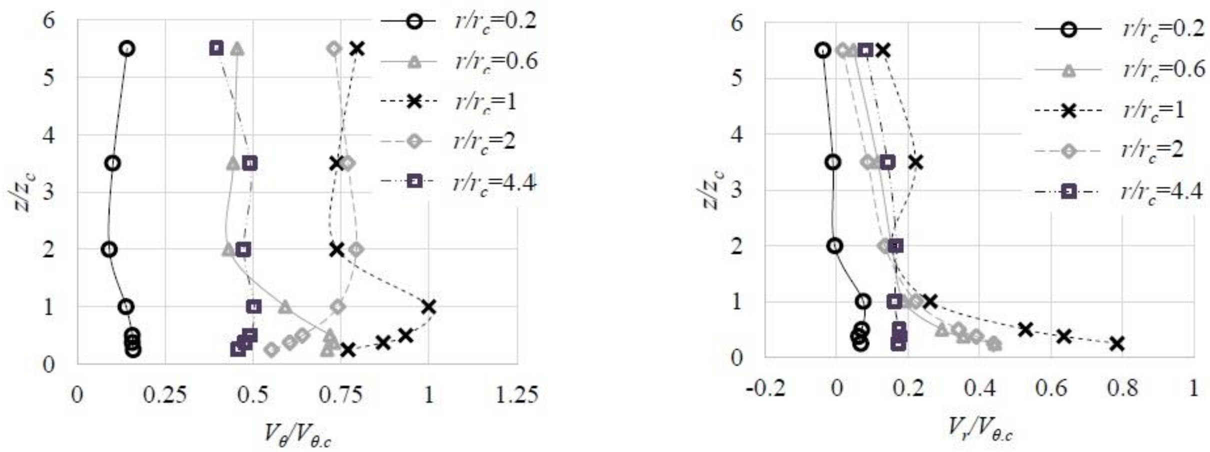
In Fig. 2, normalized radial distribution of the ground surface pressure for the stationary tornado is shown along two radial lines passing through the tornado center, along the translation direction (x) and normal (y) to this direction, exhibiting almost constant radial distribution of mean pressure coefficients around the center. This type of radial distribution of normalized ground surface pressure is comparable with those observed by Natarajan and Hangan (2012) for mid-to-high swirl ratios (S_{vane}.> 0.5), and those observed in the Mullinville, Kansas, tornado of 2002 and the Tipton, Kansas, tornado of 2008 (Karstens *et al.* 2010). The minimum mean pressure coefficient for this simulation was -1.83.

In Fig. 3, radial distribution of the mean ground surface pressure for the stationary tornado is normalized with its largest magnitude and compared with the data from the Tipton, Kansas tornado of 2008 (Karstens *et al.* 2010). Core radius for the field tornado is unknown so two core radii of 100 m and 200 m were considered for the comparison. Results show a good match between laboratory simulation and the field tornado, when the core radius of the field tornado was considered equal to 200 m.

Fig. 4 shows radial profiles of normalized mean tangential ($V_\theta/V_{\theta.c}$) and mean radial velocities ($V_r/V_{\theta.c}$) of a stationary tornado at different normalized heights above the ground plane (z/z_c), where the positive value of radial velocity is considered to be toward the center of the tornado. It is observed in Fig. 4(a) that mean tangential velocity at all heights increases with radial distance from the center of the tornado to a maximum value that occurs at around 0.8r_c to 1.4r_c, after which it decays. The normalized maximum mean tangential velocity increases with height up to z/z_c=1 (z=0.051 m) and decreases above z/z_c=1 (z=0.051 m), while the core radius increases with increase in height up to z/z_c=1 (z=0.051 m) and remains almost constant at higher elevations of z/z_c=2 and z/z_c=3.5. The maximum mean radial velocity in the flow field ($V_{r.max}$) is 0.79$V_{\theta.c}$ and occurs at the r_c, at z/z_c=0.25 (z=0.013 m) that is the lowest measurement point in this experiment, well below z_c. This is consistent with field observations using radar measurements where maximum inflow was found to occur at 30m above ground level in the Mulhall Tornado of 1999 (Lee and Wurman 2005) and at 15-30m above ground level in the Harper, Kansas, tornado of 2004 (Kosiba *et al.* 2008). In Fig. 4(b), it is observed that radial velocity increases with an increase in radial distance up to about r/r_c=1, and thereafter decreases. An increase in height, results in a steep reduction in mean radial velocity. The maximum mean radial velocity at the height corresponding to $V_{\theta.c}$ (z/z_c=1) drops to 41% of $V_{r.max}$ or 0.32$V_{\theta.c}$. Radial velocities inside the core radius at elevations greater than or equal to z/z_c=2 are about the same magnitude. For all elevations of measurement, low radial outflow was observed close to the tornado center, inside the radius of 0.2r_c., which is a sign of a two-celled tornado structure.

Fig. 5 shows vertical profiles of normalized mean tangential and normalized mean radial velocities at different normalized radial distances. It was observed in Fig. 5(a) that tangential velocity at r/r_c=4.4 (r=1.4 m) does not vary significantly with height and is less than 0.5$V_{\theta.c}$. At a smaller radial distance of r/r_c=2, ABL-like vertical profile of tangential velocity is observed with a maximum of 0.79$V_{\theta.c}$ at z/z_c=2. At r/r_c=1 or the core boundary, the appearance of a specific vertical profile of tangential velocity is observed, where maximum tangential velocity increases to its peak at z/z_c=1 and decreases above that height until it reaches an almost constant value. The peak value of maximum tangential velocity at r/r_c=1 occurs at half the elevation compared to r/r_c=2. At radial distances smaller than r/r_c=1, the tangential velocity is smaller at all heights compared to those at r/r_c=1; at r/r_c=0.6 the peak maximum tangential velocity decreased to 0.73$V_{\theta.c}$., but occurs very close to the ground plane (z/z_c=0.38).

It was seen in Fig. 5(b) that the radial velocity (inflow) at r/r_c=4.4 (far field) is lower than 0.2$V_{\theta.c}$ at all heights measured. As radial distance decreases, for example at r/r_c=2, the radial velocity decreases slightly above z/z_c=2 compared to those at r/r_c=4.4, but significantly increases at lower heights, with a peak value increasing to more than 2.5 times that of peak radial velocity at r/r_c=4.4 just above the ground plane at z/z_c=0.25.



(a) Mean *tangential* velocity (b) Mean *radial* velocity

Fig. 5 Normalized vertical profiles of mean velocity components for a stationary tornado

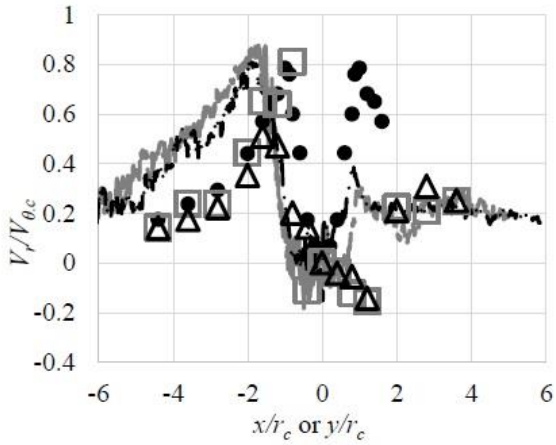
These vertical profiles of radial velocity that are specific to tornadoes were also observed by Baker (1981). At r/r_c=1, $V_{r.max}$=0.79$V_{\theta.c}$ occurs at z/z_c=0.25, the lowest height of measurement. A further decrease in radial distance results in a reduction of the radial velocity, with a reversal of radial flow direction (moving away from the center of tornado) or negative radial velocity occurring at r/r_c=0.2 above z/z_c=2, which is an indication of downdraft occurring at around the center of the core area.

Comparison of the Omni-probe velocity measurements with those from a more accurate Cobra-probe in a turbulent flow generated inside a straight-line wind tunnel showed that Omni-probe can accurately measure a mean velocity as low as 2 m/s (with < 5% error). Cobra-probe does not respond to velocities lower than 2m/s so comparison at low velocities was not possible. Velocity measurement with the Omni-probe is expected to have a greater uncertainty for mean velocities lower than 2 m/s because of its low magnitude. However, very low velocities (<2 m/s) occurred at locations (a) very close to the tornado center inside the tornado core where solid-body rotation is applicable and hence the low velocities measured can be verified with the larger velocities measured away from the center, and (b) very far from the tornado center outside the tornado core where the accuracy of the velocities may not be as important because it is much smaller than the maximum velocities in the flow field around the core.

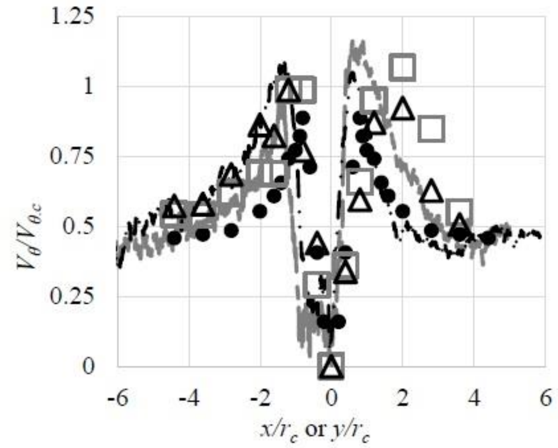
3.2 Translating tornado

To attain a better understanding of the effects of tornado's translation on the near-ground tornado flow field, comparison of radial and vertical profiles of normalized tangential and normalized radial velocities for translating tornadoes, corresponding to two translation speeds of V_t=0.15 m/s and V_t=0.50 m/s are shown along with the velocity profiles of the stationary tornado (V_t=0) in Figs. 6-8. These velocities are ensemble averaged from three velocity time histories. In Fig. 6, profiles along the translation direction (x) are shown with lines because velocity time histories are available along this direction providing high-resolution measurement (0.00075 m for translation speed of 0.15 m/s and 0.00375m for translation speed of 0.5 m/s), while profiles in y-direction are shown with symbols because velocity measurements at the grid points are discrete corresponding to Table 2, y-direction. Continuous lines are extracted from the measured time histories at *y*=0, which is the center of the rotation for the stationary tornado and is considered as the mean path of the translating tornado. This is assessed to be the closest location to the center of the rotation of the translating tornado from the streamlines of horizontal velocities at different heights as shown in Fig. 10. To extract radial and tangential velocity components in y-direction on both sides of the tornado's mean path, time of the occurrence of the center of rotation is extracted first, from the change in sign of the tangential component of velocity time history at *y*=0 and then, velocity components occurring at the same time of occurrence were extracted from time histories measured at the non-zero *y* values. All velocities were normalized with the maximum tangential velocity of the stationary tornado in the flow field ($V_{\theta.c}$=10.8 m/s).

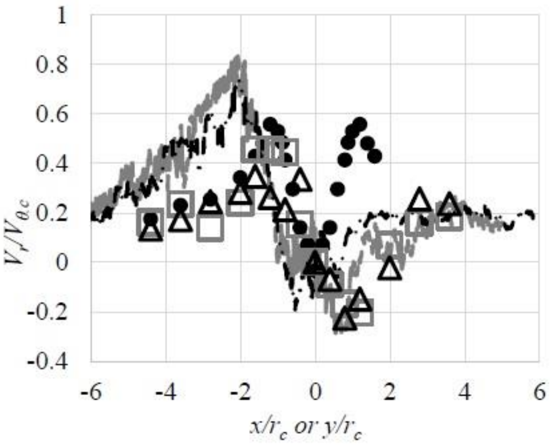
As depicted in Figs. 6(a) and 6(c), for translating tornadoes, radial velocity along the translation direction (*x*) on the front side (+x/r_c) and to the left side (+y/r_c) of the tornado center decreases significantly, and a negative radial velocity (outflow) occurs around the center of rotation along these two radial directions (+*x* and +*y*). Radial velocity along the translation direction (*x*) and behind the center of rotation (-x/r_c) increases at both elevations in comparison to that of the stationary tornado with a larger increase at z/z_c=0.50. Maximum radial velocities for translating tornadoes at both heights occur at a larger radial distance of ~2r_c. The radial velocity normal to the translation direction and to the right side of the tornado center (-y/r_c) has a magnitude comparable to that of the stationary tornado for V_t=0.15 m/s and is smaller than that of the stationary tornado for V_t=0.50 m/s.



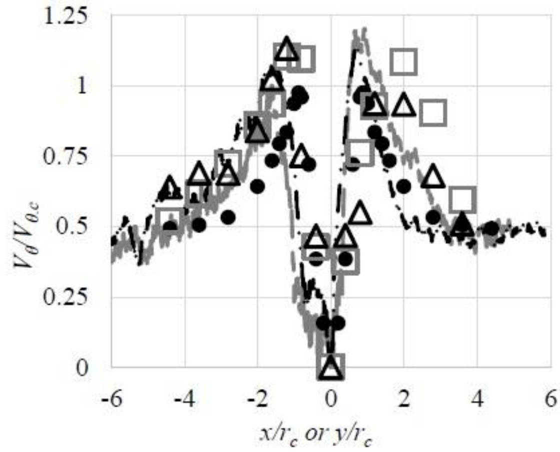
(a) Normalized *radial* velocity ($V_r/V_{\theta.c}$) at z/z_c=0.5



(b) Normalized *tangential* velocity ($V_\theta/V_{\theta.c}$) at z/z_c=0.5



(c) Normalized *radial* velocity ($V_r/V_{\theta.c}$) at z/z_c=1



(d) Normalized *tangential* velocity ($V_\theta/V_{\theta.c}$) at z/z_c=1

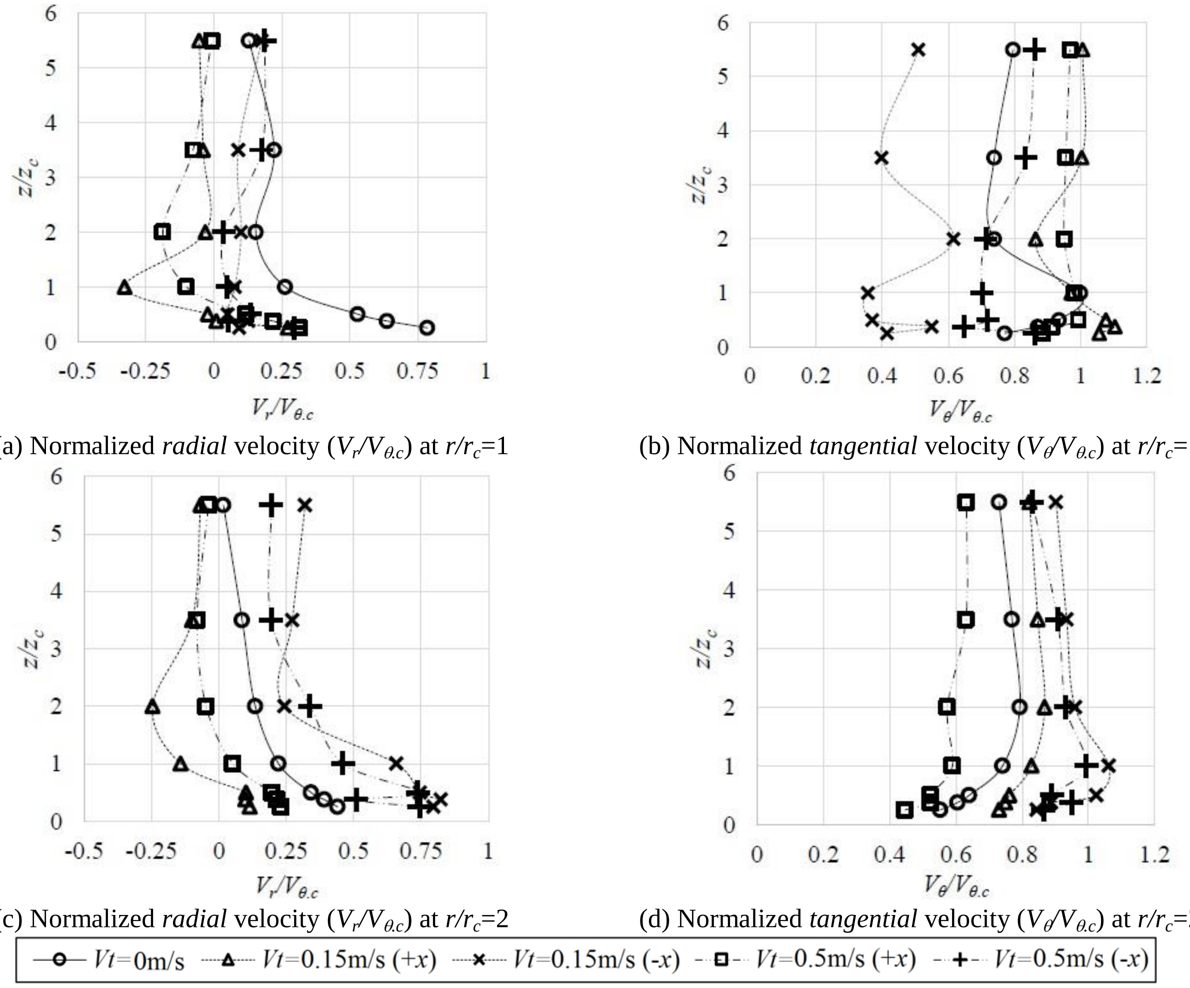
● Vt=0m/s — — Vt=0.15m/s (x) —· · Vt=0.5m/s (x) □ Vt=0.15m/s (y) △ Vt=0.5m/s (y)

Fig. 6 Radial profiles of normalized ensemble averaged *radial* and *tangential* velocities for translating tornadoes

In Figs. 6(b) and 6(d), core radius of the translating tornado r_t (radial location of maximum mean tangential velocity at each height) is larger than that of the stationary tornado (r_s) at z/z_c=0.5 and z/z_c=1. It is clear that introduction of translation results in the expansion of the core along both x and y-directions, confirming the results of Diamond and Wilkins (1984) and Liu and Ishihara (2016) that core radius of translating tornadoes increases with respect to stationary tornadoes. For the stationary tornado, r_s=0.8r_c and r_s=0.88r_c at z/z_c=0.5 and z/z_c=1, respectively.

The core expansion for the translating tornado is up to about 2.3r_c along the y-direction and on the left side of the tornado mean path (+y/r_c), and 1.6r_c along the x-direction and behind the tornado (-x/r_c), 1.4r_c along the y-direction and on the right side of tornado mean path (-y/r_c), and equal to r_c along the x-direction and on the front side of the center of rotation (+x/r_c) at z/z_c=0.5. The only difference at z/z_c=1 is that expansion of r_c along the x-direction and behind the tornado center (-x/r_c) is 1.9r_c, indicating that expansion of the core radius increases with height, at least along the x-direction. This conclusion does not match with Ishihara and Liu (2016), where addition of translation reduces the radius of maximum tangential velocity. At both elevations, z/z_c=0.5 and z/z_c=1, maximum tangential velocity along the translation direction (x) at y=0 for V_t=0.15 m/s is larger than that of V_t=0.50 m/s which in turn is larger than that of V_t=0 (stationary tornado). An increase in core radius in the translation direction, results in longer exposure of maximum winds and low ground surface pressures to any building over which the tornado passes, correlating with the observed structural damage (Wurman and Alexander 2005), while in normal to the translation direction it results in larger widths of maximum winds and low ground surface pressure, increasing the likelihood of structural damage and the width of damage path compared to very slowly moving or almost stationary tornadoes.

One important observation from Fig. 6 is that radial inflow abruptly decreases in magnitude or changes direction to become radial outflow right around the core radius. This means that, as soon as the radial inflow toward the center of rotation stops, the tangential velocity reaches its peak and thereafter decreases with a decrease in radial distance. The underlying explanation for this observation is that tangential velocity increases as radial distance decreases because of conservation of angular momentum ($L=mrV_\theta$), but occurs as long as the vortex continues to shrink that occurs only with



(a) Normalized *radial* velocity ($V_r/V_{\theta.c}$) at r/r_c=1

(b) Normalized *tangential* velocity ($V_\theta/V_{\theta.c}$) at r/r_c=1

(c) Normalized *radial* velocity ($V_r/V_{\theta.c}$) at r/r_c=2

(d) Normalized *tangential* velocity ($V_\theta/V_{\theta.c}$) at r/r_c=2

Fig. 7 Vertical profiles of normalized ensemble averaged radial and tangential velocities for translating tornadoes

a positive radial inflow. Another observation is that radial inflow changes direction between 0 to 2 core radius along both $+x/r_c$ and $+y/r_c$ directions, indicating that the downdraft center is not aligned with the center of rotation and instead, tilted toward the left side of the center of rotation for the translating tornado.

In Fig. 7(a), it is observed that radial velocity at r/r_c=1 decreases because of the translation. Except for the heights lower than ~z/z_c=0.5, radial velocity in front of the center of rotation (+*x*) changes direction at all heights for both translation speeds, which is an indication of the occurrence of a downdraft. Behind the center of rotation (-*x*), radial velocity is toward the center, but its peak is much smaller than that of the parent stationary tornado. In Fig. 7(c), it is seen that radial velocity at r/r_c=2 decreases on the front side of the center of rotation and increases behind it as a result of translation.

In Fig. 7(b), it is observed that at r/r_c=1, tangential velocity behind the center of rotation (-*x*) is less than that on the front side (+*x*), and the difference in magnitude of tangential velocity behind and on the front side of the center of rotation is more pronounced for a tornado with lower translation speed. This is not consistent with the results at r/r_c=2 as shown in Fig. 7(d) where the difference in the magnitude of tangential velocity behind and in front of the center of rotation is more pronounced for the higher translation speed. The difference in behavior of the flow at these two radial distances is because of the difference in physics of the flow inside and outside the core. While r/r_c=1 is less than or equal to the core radius of the translating tornadoes, r/r_c=2 is outside their core, feeding on the far-field angular momentum. This is not the physics behind the flow of angular momentum inside the core. This behavior can be seen in Figs. 7(c) and 7(d) at r/r_c=2, where larger radial velocities result in larger tangential velocities for the translating tornadoes compared to those of stationary case at the same location behind the center of tornado (-*x*).

In Fig. 8, normalized radial profiles of tangential velocities for stationary tornadoes are compared between the current experiment, Doppler radar data from the Spencer, South Dakota tornado of 1998 (Haan *et al*. 2008) and numerical simulation of Liu and Ishihara (2016). Comparison shows a good agreement between the normalized results from all three studies; it shows almost linear growth of tangential velocity with increase in radial distance inside the core and a decaying profile outside the core.

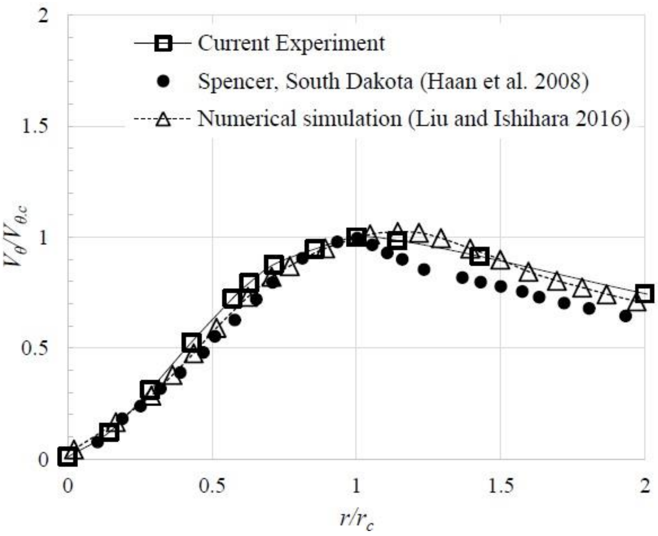
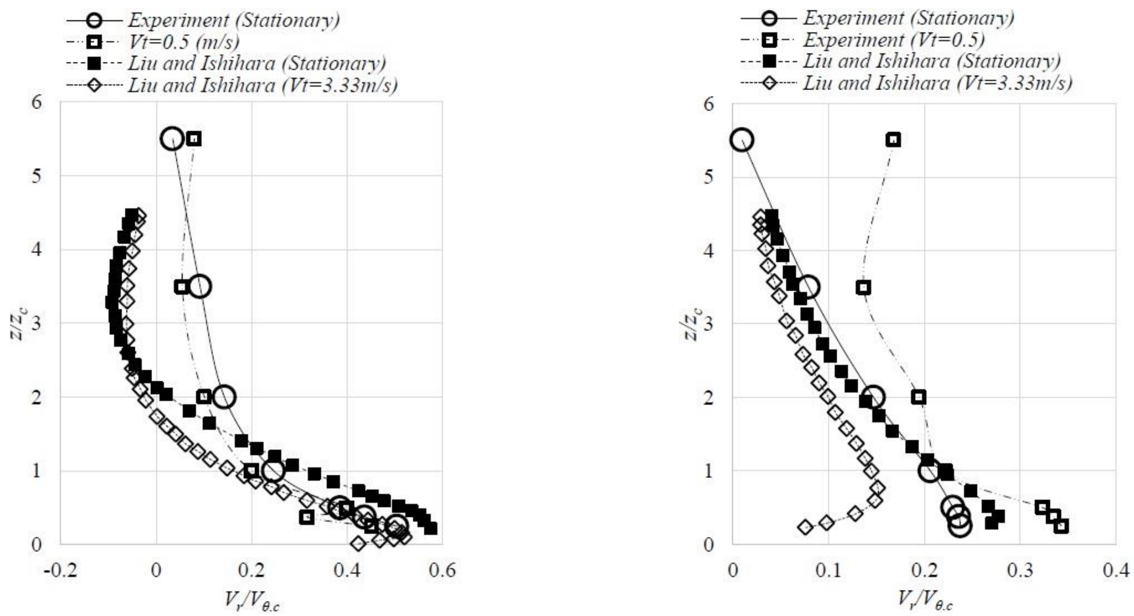


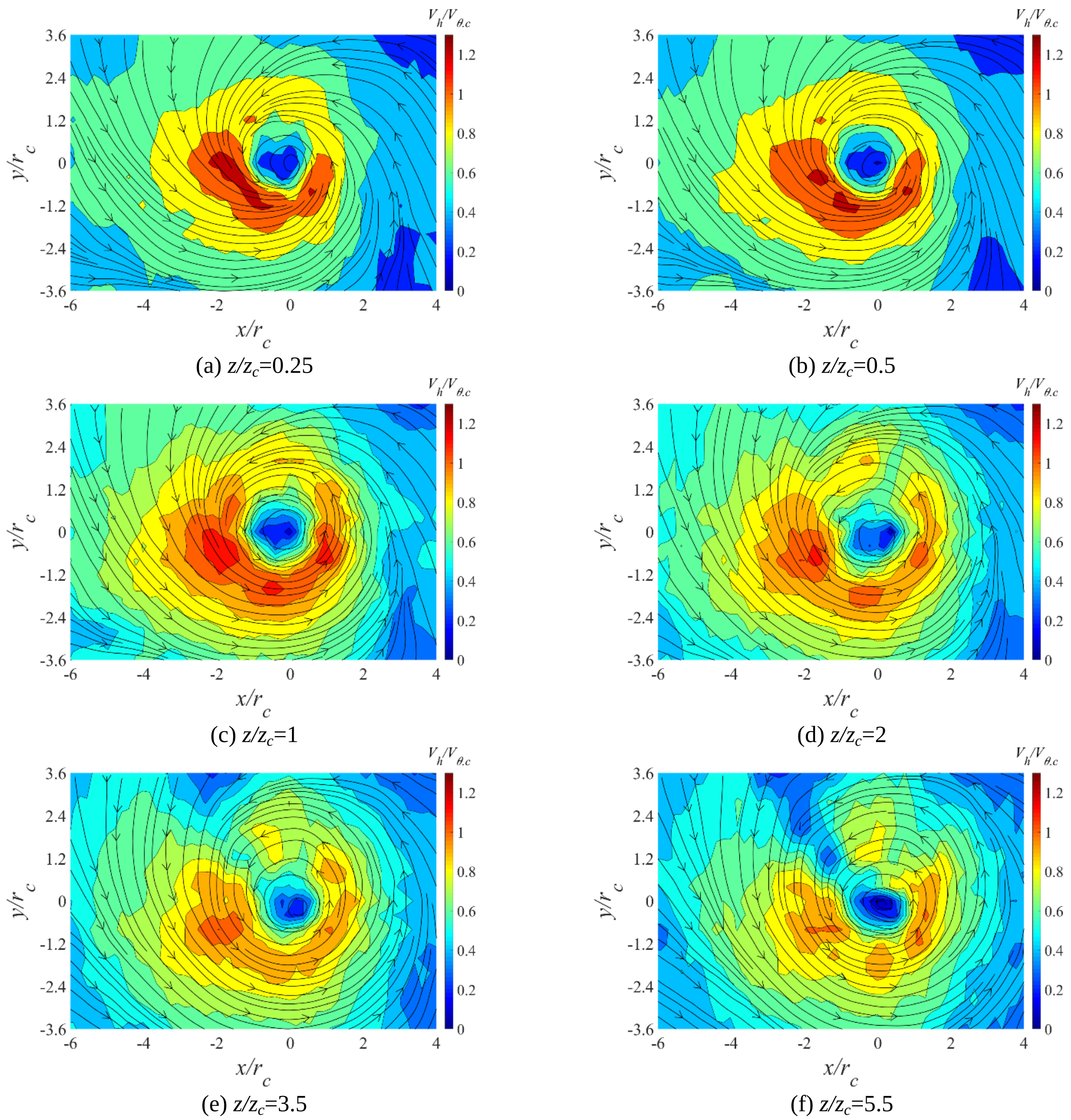
Fig. 8 Comparison of normalized radial profiles of tangential velocity at z/r_c=0.52 for numerical simulation and Doppler radar measurement and at z/r_c=0.56 for the current experiment



(a) r/r_c=1.8 (b) r/r_c=3.6

Fig. 9 Comparison of normalized *radial* velocity with numerical simulation of Liu and Ishihara (2016)

In Fig. 9, vertical profiles of normalized radial velocities are compared between the current experiment and the numerical simulation of Liu and Ishihara (2016), where relative ground motion was used to simulate translating tornadoes. In the numerical simulation, $V_{\theta.c}/V_t$=8.06, while in the current study, $V_{\theta.c}/V_t$=21.6 for V_t=0.5 m/s and $V_{\theta.c}/V_t$=72 for V_t=0.15 m/s; hence, V_t=0.5 m/s is used for the comparison. In the numerical simulation, distribution of maximum tangential velocity for translating tornado was considered axisymmetric; hence, radius of maximum tangential velocity in the cyclostrophic balance region was calculated by spatial averaging over 12 angles around the tornado center. In the experiment, lack of high resolution data at all angles around the tornado center, forced us to average the data over 2 angles only, in front and behind the tornado center. In Figs. 9(a) and 9(b), profiles of the stationary tornadoes from both experiment and numerical simulation are similar, up to z/z_c≈2 (z/r_c≈0.32) at r/r_c=1.8 and up to z/z_c≈4.5 (z/r_c≈0.72) at r/r_c=3.6. The discrepancy at r/r_c=1.8 is because of the higher swirl ratio of the numerical simulation, which results in appearance of an outflow (radial velocity moving away from the tornado center) at larger radial distances in comparison to the experimental study. At r/r_c=1.8, radial velocity of translating tornadoes decreases near the ground plane in both experimental and numerical simulations and profiles show a good agreement



(a) z/z_c=0.25 (b) z/z_c=0.5

(c) z/z_c=1 (d) z/z_c=2

(e) z/z_c=3.5 (f) z/z_c=5.5

Fig. 10 Contours and streamlines of normalized horizontal velocity ($V_h/V_{\theta.c}$) for the translating tornado with V_t=0.5 m/s

in their trend. For translating tornadoes at r/r_c=3.6, radial velocity increases in the laboratory tornado, while decreases in the numerical simulation. This may cast doubt on the accuracy of ground relative motion in simulation of translating tornadoes, at least at large radial distances. In the numerical simulation, effect of translation damps out, at about $z/z_c\approx4$ at both radial distances, which confirms Liu and Ishihara's (2016) speculation that, simulation of translating tornadoes by ground relative motion may not be valid at high elevations above the ground plane.

There are two weaknesses in the comparison between the numerical simulation and laboratory results: (a) Numerical profiles are spatially averaged over 12 angles around the tornado center, while experimental results are averaged over 2 angles only, and (b) Swirl ratios do not match between the two simulations (S_{inlet}=3.8 for Liu and Ishihara 2016 and S_{vane}=0.86).

To observe the effects of translation on tornado flow field, contours and streamlines of horizontal velocity (combination of radial and tangential velocities) for translation speed of 0.5 m/s at 6 different horizontal planes at different heights are shown in Fig. 10. The simulated translating tornado with larger translation speed is considered, since it is closer to the range of translation speeds in the field. Comparing $V_{\theta.c}$=10.8 m/s to the range of velocities in EF3 tornadoes (61 m/s to 75 m/s) results in translation speeds of V_t=0.15m/s and V_t=0.50 m/s to scale up to 0.85 m/s to 1.04 m/s and 2.82 m/s to 3.47 m/s, respectively. The low end of measured translation speed in the field is 2-3 m/s, citing an example of 2.2 m/s observed for the Manchester, South Dakota, 2003, F4-tornado (Karstens *et al.* 2010).

In Fig. 10, contours and streamlines of instantaneous horizontal velocity were mapped into the spatial domain from the time histories of horizontal velocities, using the Taylor's hypothesis. Contours were extracted from the magnitude of velocity vectors at each point of the measurement grid and extrapolated for off-grid locations. Deriving the streamlines needed the measurement of velocity vectors at each grid point because streamlines are tangent to the velocity vectors. Streamlines in between the grid points were extrapolated. In Fig. 10, instantaneous peak horizontal velocities ($V_{h.max}$) are moved toward negative x/r_c and y/r_c at all heights, compared to those of the axisymmetric stationary tornado that exhibit an axisymmetric ring of maximum velocity around the tornado center. Asymmetry in velocity magnitude of the translating tornado is more pronounced in the y-direction. Velocity contours in Fig. 10 are similar to the numerical results of Natarajan and Hangan (2012), who found that local maximas are locations of secondary vortices. In their numerical simulation, swirl ratio, taken to be 1, was defined at the inlet of the model, comparing closely to the S_{vane} value of 0.86 in this study. The difference with that study is that local maximum velocities occurred on the left side of the tornado center, while in the current study it occurred on the right side; the possible underlying reason behind this difference is the difference in the direction of the inlet tangential velocity. In the numerical study of Natajan and Hangan (2012) contours of tangential velocity are shown, that match better with Fig. 10 at higher elevations ($z/z_c \geq 2$), where the contribution of radial velocity is much smaller and horizontal velocity is closer to the tangential velocity

In Fig. 11, maximum horizontal velocities as a function of height are compared between the two translation speeds of V_t=0.15 m/s and V_t =0.5 m/s. These maximums are extracted from the analysis of all time histories at each height. Increase in translation speed reduces $V_{h.max}$ at all measured heights. Peak $V_{h.max}$ at both translation speeds occurs at z/z_c=0.38, lower than z_c, the height at which $V_{\theta.c}$ occurs, which is the result of occurrence of significant radial velocity very close to the ground plane. Peak $V_{h.max}$ for V_t=0.15 m/s is 9% larger than the corresponding peak for V_t =0.5 m/s.

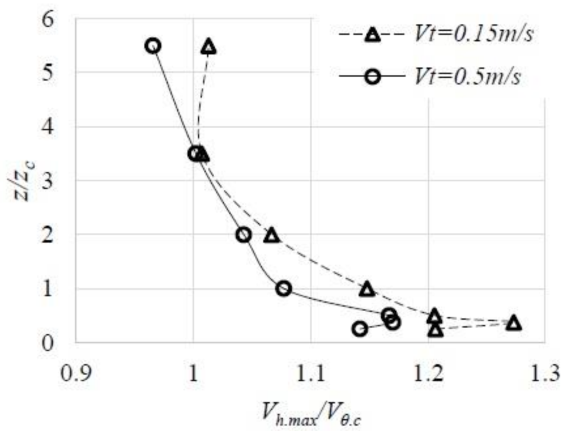


Fig. 11 Effect of translation speed on instantaneous peak horizontal velocity

4. Conclusions

In this paper, effects of translation on near-ground wind field of tornadoes were examined by simulating a translating tornado by a laboratory tornado simulator that can move over a ground plane. The effects of the translation on horizontal velocity components were observed, and compared with the parent stationary tornado. Flow field of the simulated stationary tornado showed similarity with radar-derived velocities of field tornadoes, with peak radial velocity occurring at very low elevations close to the ground (< 40 m). Specific normalized profiles of radial and tangential velocities of a stationary tornado were compared with those observed in previous radar-derived field and numerical studies and found to be similar. Compared with the flow field of a stationary tornado, the simulated tornado with translation had an influence on the spatial distribution and magnitude of the horizontal velocities, early reversal of the radial inflow, and expansion of the core radius. The implication of an increase in core radius is that it increases the regions of high velocities and minimum pressure drops along normal to the translation direction, and duration of large velocities and minimum pressure drops in the translation direction, both increasing the possibility of damage. Comparison of vertical profiles of radial velocities for translating tornadoes, between the two approaches of relative motion of the ground plane and translation of the tornado simulator, showed good agreement in trends at smaller radial distances to the tornado center, while a mismatch in behavior at larger radial distances. In numerical simulation of translating tornado using the relative motion of the ground plane, as in a previous study (Liu and Ishihara 2016), profiles of radial velocities for stationary and translating tornadoes coincide and effect of translation vanishes at elevations higher than z/z_c=4. In the current study, at a larger radial distance of r/r_c=3.6, profiles of radial velocity for a translating versus a stationary tornado show a significant difference at all elevations except z/z_c=1. This comparison casts a doubt on the accuracy of relative motion of the ground plane in simulation of a translating tornado flow field. Finally, it was observed that increase in translation speed resulted in a decrease in maximum horizontal velocities at all heights.

Acknowledgments

This study was supported by the US National Science Foundation (NSF) under award number CMMI-1400251.

References

Baker G.L. (1981), Boundary layers in laminar vortex flows, Ph.D. dissertation; Purdue University, West Lafayette, Indiana, USA.
Church C.R., Snow J.T., Baker G.L. and Agee E.M. (1979),

"Characteristics of tornado-like vortices as a function of swirl ratio: a laboratory investigation", *J. Atmos. Sci.*, **36**, 1755-1776.

Davies-Jones R.P. (1973), "The dependence of core radius on swirl ratio in a tornado simulator", *J. Atmos. Sci*., **30**, 1427-1430.

Dessens Jr. J. (1972), "Influence of ground roughness on tornadoes. A laboratory simulation", *J. Appl. Meteorol.*, **11**, 72-75.

Diamond C.J. and Wilkins E.M. (1984), "Translation effects on simulated tornadoes", *J. Atmos. Sci*., **41**(17), 2574-2580.

Haan Jr. F.L., Sarkar P.P. and Gallus W.A. (2008), "Design, construction and performance of a large tornado simulator for wind engineering applications", *Eng. Struct.*, **30**, 1146-1159.

Hashemi Tari P., Gurka R. and Hangan H. (2010), "Experimental investigation of tornado-like vortex dynamics with swirl ratio: The mean and turbulent flow fields. *J. Wind Eng. Ind. Aerod*., **98**(12), 936-944.

Jischke M.C. and Parang M. (1974), "Properties of simulated tornado-like vortices", *J. Atmos. Sci*., **34**, 1022-1027.

Karstens C.D., Samaras T.M., Lee B.D. and Finley C.A. (2010), "Near-ground pressure and wind measurements in tornadoes", *Mon. Weather Rev*., **138**, 2570-2588.

Kosiba K.A., Trapp R.J. and Wurman J. (2008), "An analysis of the axisymmetric three-dimensional low-level wind field in a tornado using mobile radar observation", *Geophys. Res. Lett.*, **35**, L05805, 1-6. doi:10.1029/2007GL031851.

Lee W. and Wurman J. (2005), "Diagnosed three-dimensional axisymmetric structure of the Mulhall tornado on 3 May 1999", *J. Atmos. Sci*., **62**, 2373-2393.

Leslie F.W. (1977), "Surface roughness effects on suction vortex formation: a laboratory simulation", *J. Atmos. Sci.*, **34**, 1022-1027.

Lewellen W.S. (1963), "A solution for three-dimensional vortex flows with strong circulation", *J. Fluid. Mech.*, **14**, 420-432.

Lewellen W.S., Lewellen D.C. and Sykes R.I. (1997)), "Large-eddy simulation of a tornado's interaction with the surface", *J. Atmos. Sci.*, **54**(5), 581-605.

Liu Z. and Ishihara T. (2016), "Study f the effects of translation and roughness on tornado-like vortices by large-eddy simulation", *J. Wind Eng. Ind. Aerod*., **151**, 1-24.

Natarajan D. and Hangan H. (2012), "Large eddy simulation of translation and surface roughness effects on tornado-like vortices", *J. Wind. Eng. Ind. Aerod.*, **104-106**, 577-584.

Razavi A. and Sarkar P. (2016), "Laboratory investigation of the effects of tornado translation on its near-ground flow field", *Proceedings of the 8th international colloquium on bluff body aerodynamics and applications,* June 7-11, Boston, Massachusetts, USA.

Refan M. and Hangan H. (2016), "Characterization of tornado-like flow fields in a new model scale wind testing chamber", *J. Wind Eng. Ind. Aerod.*, **151**, 107-121.

Rotunno R. (1977), "Numerical simulation of a laboratory vortex", *J. Atmos. Sci*., **34**, 1942-1956.

Ward N.B. (1972), "The exploration of certain features of tornado dynamics using a laboratory model", *J. Atmos. Sci.*, **29**, 1194-1204.

Wurman J. and Alexander C.R. (2005), "The 30 May 1999 Spencer, South Dakota, storm. Part II: comparison of observed damage and radar-derived winds in the tornadoes", *Mon. Weather Rev*., **133**, 97-119.