Numerical modeling of debris flight in a one-cell tornado wind field

Ali Tohidi

* Mechanical Engineering Department, San José State University, San José, CA, USA. ali.tohidi@sjsu.edu

ABSTRACT:
The windborne debris flight in strong wind fields of tornadoes is known to contribute significantly to the incurred damages. Previously, there has been a considerable amount of work done on the flight trajectory and impact of compact and plate-like debris in such wind fields. However, less attention has been paid to the flight path of rod-like debris. This study numerically models the trajectory of rod shape debris in the a one-cell tornado wind field and compares the results with trajectories of mass equivalent particles with different shapes, that is compact, and plate shapes. The preliminary results show the importance and effects of rotational motion on the flight path of rod-like debris compared to the mass equivalent compact debris with the same initial conditions. The present work conducts a set of stochastic simulations and characterizes the effects of shape on the flight path, landing distribution, and energy of impact upon landing.

Keywords: Wind-borne, debris, Tornado, Flight Path, Stochastic, Deterministic

1. INTRODUCTION
Tornadoes present a powerful whirling column of air that is bounded by the surface of the earth at the bottom and, usually, cumulonimbus clouds at the top. Each year in the United States more tornadoes occur than in any other country (Dotzek, 2003). NOAA’s Storm Prediction Centre, reported 1,053 tornadoes in 2020, which is over three times the average of the reported cases in Europe (Dotzek 2003 & NOAA 2021). Most tornadoes generate wind speeds between 15-50 m/s but, in extreme cases, the velocity can reach more than 100 m/s (Baker & Sterling, 2017). Such winds not only cause different loading mechanism on the structures (Baker & Sterling, 2017), that may lead to structural damages, but also loft debris that is often visible as a rotating cloud around the tornado base. The impact energy of the lofted debris and their subsequent penetration to the structural elements are recognized to contribute significantly to the incurred damages (Grayson et al., 2012). For instance, the January 2020 tornadoes in the U.S., caused substantial property loss across multiple states and led to numerous injuries, and 10 fatalities (Smith, 2021). Thus, in order to better estimate the risks from tornadoes and, devise and improve on the existing tornado preparedness plans, it is important to characterize the amount of energy and radius of impact from lofted debris to the built environment during such wind events.

To this end, the flight path of debris needs to be resolved in the tornado-generated velocity field. The trajectories depend on the physical properties of the particles such as density, initial mass, geometric characteristics, namely shape and aspect ratio, initial release angles, and the turbulence characteristics of the ambient wind field (Kordi & Kopp, 2011). Previous studies have mostly investigated the trajectories of compact debris (Karimpour & Kaye, 2011; Liu et al., 2021) and plate-like debris (Kordi & Kopp, 2011) and little attention has been paid to the dispersion of rod-like debris in wind events. The existing literature on tornado wind fields, however, is rich; there is a large volume of published studies on the velocity field description and its turbulent characteristics. In the present work, we study the effects of particle geometry (shape and aspect ratio), and the initial release angles on the trajectories of rod-like debris compared to the
compact and plate-like ones with the same mass. Since the aim of the study is to investigate the effects of shape and initial release angles on the flight path, the ambient tornado-generated wind field is modelled using a simple one-cell tornado model proposed by (Baker & Sterling, 2017) without considering any turbulence effects.

2. TORNADO WIND FIELD AND DEBRIS TRANSPORT MODELS
Although multi-cell tornados are more common than one-cell tornados (Baker & Sterling, 2017), one-cell model is adopted to reduce the complications that multi-cell tornado velocity field may induce in the resolved trajectories. The model efficiently simulates the tangential, radial, and axial velocity profiles for both forced and free-vortex regions and is validated against experimental data (Refan et al., 2014). Figure 1-(a), shows the wind velocity profiles of a one-cell tornado over open/grass land.

The trajectory of non-compact particles is often complicated which subsequently affects their flight range and landing distribution. Thus, a transport model that solves the governing equations of motion for non-compact particles in a fully deterministic 3D 6-degrees-of-freedom (DOF) mode is adopted; refer to (Grayson et al., 2012) for details. Also, the transport model incorporates the experimentally measured steady aerodynamic force and moment coefficients of (Richards et al., 2008). In a more recent study (Tohidi & Kaye, 2017b), modified the model to conduct stochastic simulations of the rod-like particles and experimentally validated the results (Tohidi & Kaye, 2017a). The transport model uses a one-way coupling approach to extract ambient velocity components, i.e., \((U, V, W)\), from the tornado wind field.

3. SIMULATIONS AND RESULTS
The modelled tornado wind has maximum tangential velocity of 50 m/s at the core radius of 50 m with swirl ratio, \(S = \frac{V_m}{U_m}\), one; where \(V_m\) and \(U_m\) are, respectively, the maximum tangential and radial velocities that occur at the core radius. The boundary layer thickness is calculated, based on the method of (Gjøsund, 2012) and data provided in (Baker & Sterling, 2017), for surface roughness of \(z_0 = 0.03\) which corresponds to open flat terrain or grass land with few obstacles (Cermak & others, 1999). The initial release position is considered to be at the core radius, i.e. \((x_0 = 50 \text{ m}, y_0 = 0)\), and well over the boundary layer thickness \((z_0 = 10 \text{ m})\). The rest of the initial conditions for the simulation are shown in Table 1.

Table 1. Initial conditions of the simulations. Here, \((\theta_x, \theta_y, \theta_z)\) are Tait–Brayan angles of the particles.

<table>
<thead>
<tr>
<th>Debris geometry</th>
<th>Density ([\text{kg/m}^3])</th>
<th>Aspect ratio, (L_{\text{max}}/L_{\text{min}})</th>
<th>Characteristic length ([m])</th>
<th>Tait-Brayan angles ((\theta_x, \theta_y, \theta_z)) ([\text{rad}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact</td>
<td>320</td>
<td>1</td>
<td>0.05</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>Plate</td>
<td>320</td>
<td>4</td>
<td>0.02</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>Rod</td>
<td>320</td>
<td>16</td>
<td>0.02</td>
<td>0, 0, 0</td>
</tr>
</tbody>
</table>

It should be noted that the physical properties of debris are chosen such that they have the same mass. Simulations are conducted with time interval of 0.01 s until the particle contact the ground. The time integration is done using modified Euler method introduced in (Grayson et al., 2012). Figure 1- (b, c), respectively, shows the resolved trajectories for a compact and rod-like debris that are release from the same position, i.e. \((x_0 = 50 \text{ m}, y_0 = 0)\), with the same random release angles.

The preliminary results show the importance of rotational effects on the trajectory of the rod shape particles. We propose to conduct a comprehensive stochastic simulation in order to capture the average behavior of the flight path of rod-like debris compared to the compact and plate-like ones in one-cell tornado wind field.
compact and plate-like ones with the same mass. Since the aim of the study is to investigate the effects of shape and initial release angles on the flight path, the ambient tornado-generated wind field is modelled using a simple one-cell tornado model proposed by (Baker & Sterling, 2017) without considering any turbulence effects.

2. TORNADO WIND FIELD AND DEBRIS TRANSPORT MODELS
Although multi-cell tornados are more common than one-cell tornados (Baker & Sterling, 2017), one-cell model is adopted to reduce the complications that multi-cell tornado velocity field may induce in the resolved trajectories. The model efficiently simulates the tangential, radial, and axial velocity profiles for both forced and free-vortex regions and is validated against experimental data (Refan et al., 2014). Figure 1-(a), shows the wind velocity profiles of a one-cell tornado over open/grass land.

The trajectory of non-compact particles is often complicated which subsequently affects their flight range and landing distribution. Thus, a transport model that solves the governing equations of motion for non-compact particles in a fully deterministic 3D 6-degrees-of-freedom (DOF) mode is adopted; refer to (Grayson et al., 2012) for details. Also, the transport model incorporates the experimentally measured steady aerodynamic force and moment coefficients of (Richards et al., 2008). In a more recent study (Tohidi & Kaye, 2017b), modified the model to conduct stochastic simulations of the rod-like particles and experimentally validated the results (Tohidi & Kaye, 2017a). The transport model uses a one-way coupling approach to extract ambient velocity components, i.e., $\langle U, V, W \rangle$, from the tornado wind field.

3. SIMULATIONS AND RESULTS
The modelled tornado wind has maximum tangential velocity of 50 m/s at the core radius of 50 m with swirl ratio, $S = V_m/U_m$, one; where $V_m$ and $U_m$ are, respectively, the maximum tangential and radial velocities that occur at the core radius. The boundary layer thickness is calculated, based on the method of (Gjøsund, 2012) and data provided in (Baker & Sterling, 2017), for surface roughness of $z_0 = 0.03$ which corresponds to open flat terrain or grass land with few obstacles (Cermak & others, 1999). The initial release position is considered to be at the core radius, i.e. $(x_0 = 50 \, m, y_0 = 0 \, m)$, and well over the boundary layer thickness $(z_0 = 10 \, m)$. The rest of the initial conditions for the simulation are shown in Table 1.

<table>
<thead>
<tr>
<th>Debris geometry</th>
<th>Density $[kg/m^3]$</th>
<th>Aspect ratio, $L_{max}/L_{min}$</th>
<th>Characteristic length $[m]$</th>
<th>Tait-Brayan angles $(\theta_x, \theta_y, \theta_z)$ $[rad]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact</td>
<td>320</td>
<td>1</td>
<td>0.05</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>Plate</td>
<td>320</td>
<td>4</td>
<td>0.02</td>
<td>0, 0, 0 $\sim$ [0, 2π]</td>
</tr>
<tr>
<td>Rod</td>
<td>320</td>
<td>16</td>
<td>0.02</td>
<td>0, 0, 0 $\sim$ [0, 2π]</td>
</tr>
</tbody>
</table>

Table 1. Initial conditions of the simulations. Here, $(\theta_x, \theta_y, \theta_z)$ are Tait–Brayan angles of the particles.

It should be noted that the physical properties of debris are chosen such that they have the same mass. Simulations are conducted with time interval of 0.01 s until the particle contact the ground. The time integration is done using modified Euler method introduced in (Grayson et al., 2012). Figure 1- (b, c), respectively, shows the resolved trajectories for a compact and rod-like debris that are release from the same position, i.e. $(x_0 = 50 \, m, y_0 = 0 \, m, z_0 = 10 \, m)$, with the same random release angles.

The preliminary results show the importance of rotational effects on the trajectory of the rod shape particles. We propose to conduct a comprehensive stochastic simulation in order to capture the average behavior of the flight path of rod-like debris compared to the compact and plate-like ones in one-cell tornado wind field.
Figure 1. Shown are (a) dimensionless velocity field of the one-cell tornado and, trajectory of a compact (b) and rod-like (c) debris that are release from the same release position with random initial release angles.

REFERENCES


