Modeling windborne debris trajectories in tornadoes

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ABSTRACT
To ensure the safety of residential communities in the event of a tornado strike it is required to consider the impact of windborne debris. Therefore, it is important to estimate both the landing location of windborne debris as well as their energy/momentum upon landing. These estimates can be carried out using a three-dimensional (3D) six-degree-of-freedom (6DOF) debris trajectory model. However, existing 3D 6DOF models focus on estimating the debris trajectory in straight-line winds. This research presents a 3D 6DOF debris trajectory model for describing the flight of windborne debris in tornadoes. The proposed solution strategy is based on a predictor-corrector time-marching scheme which solves the equations of motion for each time step while updating the wind field from an appropriate tornado wind model. The proposed strategy is then used to show the significant difference in modeling the debris trajectories in tornado wind fields as compared to straight-line winds.

Keywords: Windborne debris; Tornadoes; Debris Trajectory Modeling; Debris Impact

1. INTRODUCTION

Existing six-degree-of-freedom debris trajectory models are developed for straight-line wind which is a wind field that has predominant wind speed and direction over the debris flight time (e.g., Richards et al., 2009). This assumption is reasonable for modeling the flight of debris in hurricanes since they are generally characterized by a relatively slow rate of change in wind speed and direction. This behavior cannot be assumed for tornadoes that are transitory in nature and will generally produce rapid changes in wind direction. Therefore, this research presents a 6DOF debris trajectory model for tornado wind fields.

2. EQUATIONS OF MOTION

A flying debris object can be assumed as a rigid body in space, therefore six degrees of freedom are required to describe its motion. Based on the debris geometric classification provided by (Minor, 1994), the rectangular hexahedron in Fig. 1 is used to model the geometry of the debris objects of interest. The object is subjected to gravity and aerodynamic forces. Under these forces, the equations of motion can be written as follows,

$$m\dot{\mathbf{V}}_D = \mathbf{F}_{aero} - mg\mathbf{i}_2 \quad (1)$$

$$\dot{\mathbf{L}}_p = \mathbf{M}_{aero} + \mathbf{M}_D - \boldsymbol{\omega} \times \mathbf{L}_p \quad (2)$$

where m is the mass of the debris object; $\mathbf{V}_D$ and $\boldsymbol{\omega}$ are the debris translational and rotational velocities; g is the magnitude of the gravitational acceleration; $\mathbf{i}_2$ is the unit vector of the axes; $\mathbf{L}_p$ is the angular momentum vector of the debris object; $\mathbf{M}_{aero}$ is the aerodynamic moment; $\mathbf{M}_D$ is the damping moment introduced by (Richards et al., 2009) to prevent unbounded debris rotation.

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Equations 1 and 2 are solved using a predictor-corrector time marching scheme (Abdelhady et al., 2021). To estimate the aerodynamic forces and moments, tornado wind velocity is required. The tornado wind velocity is estimated using the tornado wind field model introduced by Baker et al., (2020).

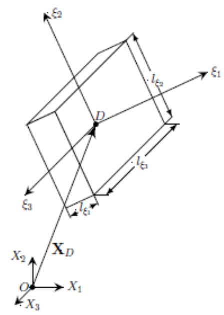

Figure 1. Reference systems used for describing the debris trajectory.

3. APPLICATION

The 6DOF trajectory model is used to estimate the trajectory of a typical roof sheathing subject to a tornado as shown in Fig. 2 (a). The tornado properties are: maximum circumferential velocity = 80 m/s, maximum radial velocity = 20 m/s, translational velocity = 4 m/s, and radius to maximum circumferential velocity (R) = 200 m. The tornado track is positioned such that $|X_{T3}|/R = 1$. Figure 2 (b) shows the significant difference between the trajectories generated using the tornado wind field as opposed to a straight wind field. This significant difference emphasizes the need for developing trajectory models for tornado wind fields.

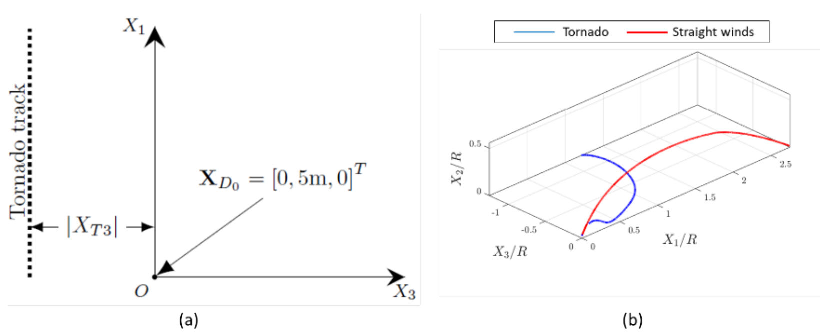

Figure 2. (a) Layout of the application problem; (b) debris trajectories for a straight and tornado wind.

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