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A tornadic field retrieval method based on wind-induced debris video-analysis

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SUMMARY:
Near-surface wind field estimation is critical for tornado-based design. Considering the intensity and randomness of the tornado events, it is challenging to directly obtain tornadic wind fields from measuring instruments such as an anemometer. However, the wind-induced debris trajectories provide an indirect observing method for the tornadic wind field. In tornadoes, windborne debris is commonly observed and recorded as videos. The windborne debris trajectories, which can be recognized through videos, can act as a probe in the wind field and reflect the physical information. This paper raises a novel model for identifying windborne debris trajectories from videos during a tornado with image analysis. Streamlines of the event are then simulated. Furthermore, a numerical 3D wind field model is established based on the debris information and can be applied to reconstruct the tornadic wind field. As a result, the Andover, KS, USA 2022 tornado is applied as an example for providing near-surface wind field estimation.

Keywords: Near-surface wind field; Tornadoes; Windborne Debris; Video Analysis

1. INTRODUCTION

In tornadoes, windborne debris is common, and the debris will obtain massive kinetic energy as missiles during the motion in the near-surface tornadic field (Lin et al., 2007; Twisdale et al., 1979). Hence, the debris trajectories will contain information on tornadic wind fields, and it is possible to consider the windborne debris trajectories as evidence for reconstructing the near-surface tornadic field. In this paper, Section 2 introduces the acquisition process of the in-situ debris trajectories data from videos collected from social media; Section 3 presents the tornadic field streamline estimation; Section 4 puts forward a method for applying single-cell vortex numerical models to estimate the debris trajectories. After comparing with the practical data, a best-fit parameter set for the vortex model is developed. Finally, the model fitting and approximation process with the Andover, KS, USA 2022 tornado is an example.

2. DEBRIS TRAJECTORY RECOGNITION

The debris trajectory recognition process is illustrated in Figure 1. In the example, the frames of the in-situ video are classified into three regions: Outer region (Blue border), where the flow is assumed forced by the vortex; Core region (Red border), where the significant rotational flow occurs; Near-surface region (Green Region), where the flow is disturbed, and debris will generate. Then, the pixel area for the potential windborne debris will be recognized for each region at each frame based on image analysis. Then, the centroid for each debris is tracked during the video and recorded as the trajectories. Furthermore, the velocity and acceleration for each debris can be calculated in the pixel-wise unit.

Figure 1. Debris recognition process for the beginning and ending frame of a video of the Andover, KS, 2022 tornado

Based on the observed data, the vortex information can be retrieved by the core region's debris trajectories, which are forced by the rotational flow and have a variant acceleration. The debris properties, like drag coefficients and Tachikawa parameter (Tachikawa, 1983), can be estimated from the trajectories in the outer region with a more stable acceleration dominated by gravity and steady flow drag effect. In addition, the information in the near-surface region can estimate the critical speed at the debris generation timestamp, which will be studied with the comparison with experimental data in the future.

3. TORNADIC FIELD RETREVIAL

The stereo coordinates can be reconstructed based on the SFM (Structure from Motion) on multiple in-situ cameras. With the reference value from the practical length of the buildings captured in the videos, the debris trajectories can be converted into a projection coordinate system, as shown in Figure 2.

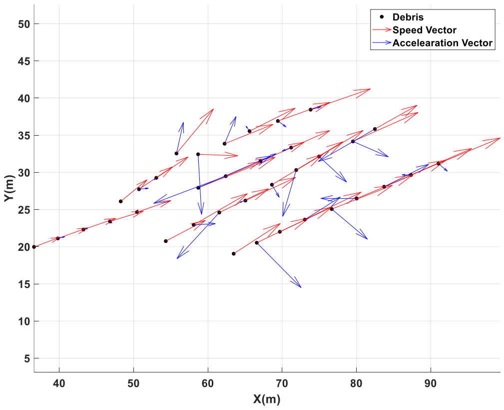

Figure 2. Illustration of the debris information in the projection coordinate system

Then, the debris can act as a probe at each frame time stamp for measuring the flow velocity and direction. Windborne debris is classified into three types: compact, sheet, and rod, based on its shape (Wills et al., 2002). As a simple illustration, basic equations of motion about debris are established only considering the compact particles' drag force (McDonald, 1976). As shown in Figure 3, the flow components **W** and **V** for a timestamp can be solved by substituting the debris motion velocity $\boldsymbol{V_x}$, $\boldsymbol{V_y}$ and acceleration $\boldsymbol{a_x}$ and $\boldsymbol{a_y}$ as Eq. (1).

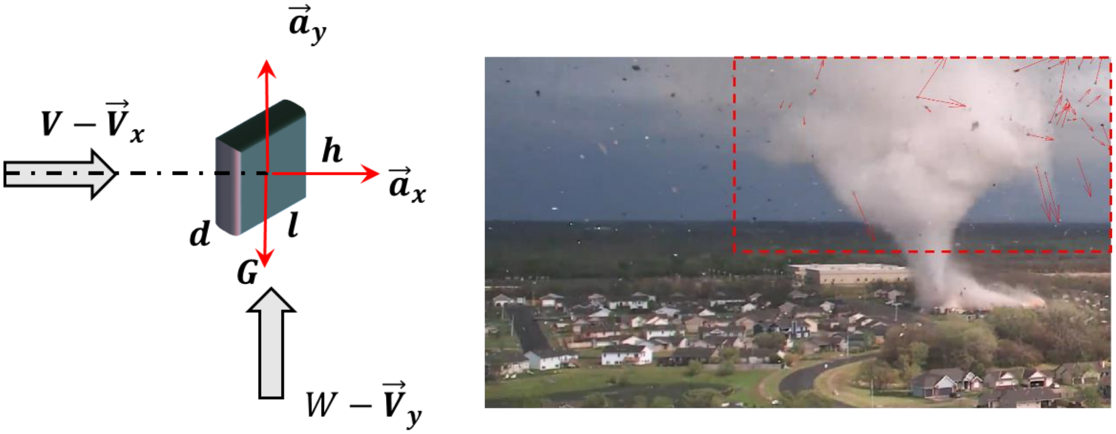

Figure 3. The schematic drawing of wind flow azimuth and all loading effects on debris in 2D view (left), the calculated flow in the core region at the starting frame (right)

$$\vec{a}_x = \frac{1}{2}\rho_a C_{Dx} hd(V - V_x)^2$$

$$\vec{a}_y = \frac{1}{2}\rho_a C_{Dy} ld(W - V_y)^2 - g \tag{1}$$

4. NUMERICAL VORTEX MODEL BASED ON DEBRIS TRAJECTORIES

Since the one-dimensional information is lost in the projection coordinates, a 3D numerical model is raised to estimate the tornadic field with the following assumptions:

- Steady-state vortex ($\boldsymbol{u_r}$, $\boldsymbol{u_z}$, and $\boldsymbol{u_\theta}$ unchanged)
- Single-cell axis-symmetric structure
- Core region: $u_r = (r/R_{max})u_{max}$
- Outer region: $u_r = (R_{max}/r)u_{max}$
- The angle between the $\boldsymbol{u_r}$ and $\boldsymbol{u_\theta}$ is a constant α
- The ratio between the $\boldsymbol{u_r}$ and $\boldsymbol{u_\theta}$ is a constant S
- Continuity Equation $\partial u_r/\partial r + u_r/r + \partial u_z/\partial z = 0$
- Momentum Equation $u_r\, \partial u_\theta/\partial r + u_z\, \partial u_\theta/\partial r + u_r u_\theta/r = 0$

Then, the vortex field is estimated with a parameter set (α, S, R_{max}, u_{max}) for simulating the equations of motion of the debris as Eq. (2) in the vortex cylindrical coordinates.

$$\frac{d^2 r}{dt^2} = \frac{\rho_a C_D A(u_r - U_m)\sqrt{(u_r - U_m)^2 + (u_z - V_m)^2 + (u_\theta - W_m)^2}}{2\rho_m D}$$

$$r\frac{d^2 \theta}{dt^2} = \frac{\rho_a C_D A(u_\theta - W_m)\sqrt{(u_r - U_m)^2 + (u_z - V_m)^2 + (u_\theta - W_m)^2}}{2\rho_m D}$$

$$\frac{d^2z}{dt^2} = \frac{\rho_a C_D A(u_z - V_m)\sqrt{(u_r - U_m)^2 + (u_z - V_m)^2 + (u_\theta - W_m)^2}}{2\rho_m D} \qquad (2)$$

Based on the comparison with the practical trajectories in the projection coordinates, a best-fit parameter is selected to generate the vortex field.

5. CONCLUSION

This abstract presents a philosophy for estimating the near-surface tornado wind field based on the debris information extracted from videos. This method reconstructs the three-dimensional wind field without direct measuring data and calculates the trajectories of the wind-induced debris.

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REFERENCES

Lin, N., Holmes, J.D., Letchford, C.W., 2007. Trajectories of Windborne Debris in Horizontal Winds and Applications to Impact Testing. Journal of Structural Engineering 133, 274–282. https://doi.org/10.1061/(ASCE)0733-9445(2007)133:2(274)

McDonald, J.R., 1976. Tornado-generated missiles and their effects, in: Proceedings of the Symposium on Tornadoes. pp. 331–348.

Twisdale, L.A., Dunn, W.L., Davis, T.L., 1979. Tornado missile transport analysis. Nuclear Engineering and Design 51, 295–308. https://doi.org/10.1016/0029-5493(79)90096-7

Wills, J.A.B., Lee, B.E., Wyatt, T.A., 2002. A model of windborne debris damage. Journal of Wind Engineering and Industrial Aerodynamics 90, 555–565. https://doi.org/10.1016/S0167-6105(01)00197-0