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Exploiting Videos to Estimate Near-Surface Wind and Debris Speed during Non-Synoptic Wind Events

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SUMMARY:
Non-synoptic wind events like tornadoes and downbursts cause billions of dollars worth of property losses each year in the United States. These wind events have revealed weaknesses in the communities they have impacted, increasing the need for wind design codes and standards to progress toward the inclusion of these wind events. To achieve this inclusion, it is critical to understand the near-surface wind and debris characteristics of these wind events. This study presents a framework for estimating near-surface wind and debris speed during non-synoptic wind events from existing wind-borne debris flight videos. The proposed framework involves three key steps: (1) accurate extraction of debris trajectories from videos in 2D or 3D space as a function of time, (2) estimation of debris attributes relevant to debris-flight motion (e.g., mass, area, aerodynamic coefficients) from the video, and (3) application of equations of motion to (1) and (2) to infer a wind speed estimate. This study shows the possibility of a physics-based approach to estimate the wind speed from wind-borne debris flight trajectory extracted from the videos.

Keywords: Wind-borne debris, Non-synoptic wind, Wind speed

1. INTRODUCTION

Non-synoptic wind events, which include thunderstorms, downbursts, and tornadoes, account for most weather-related fatalities in the United States and cost billions of dollars in property damage each year (NOAA 2021). In addition to the monetary losses, non-synoptic wind occurrences have frequently exposed weaknesses in the resilience of the communities they have impacted (Kuligowski et al. 2013). Although there has been progress towards incorporating non-synoptic winds into wind design codes and standards, a critical hindrance is the lack of understanding of near-surface wind and debris characteristics of these wind events.

This study aims to establish a framework for inferring near-surface wind characteristics from debris speed and other debris attributes captured by videos and other media during non-synoptic wind events. This extended abstract focuses on the use of unstructured debris flight media (existing videos) of these non-synoptic wind events. Also, efforts are described related to capturing structured debris flight media from future experimental testing at the NHERI Wall of Wind (WOW) shared-use facility at Florida International University.

2. WIND SPEED ESTIMATION FROM DEBRIS FLIGHT VIDEO

Inferring wind speed estimates from the captured motion of wind-borne debris requires that (1) the trajectory of the debris are accurately extracted from the video in 2D or 3D space as a function of time; (2) the attributes of the debris relevant to debris-flight motion (e.g., mass, area, aerodynamic coefficients) are reasonably estimated from the video; and (3) the equations of motion are applied to (1) and (2) to infer a wind speed estimate.

2.1 Estimation of Real Coordinates of Wind-Borne Debris Trajectory

The wind-borne debris was identified and tracked manually using Computer Vision Annotation Tool (CVAT), and the real coordinates of the debris trajectory relative to a reference point in the flight video were estimated using the fundamentals of lens optics.(Chakravarti and Siegel 2001).

$$\frac{object\ height\ on\ sensor\ (mm)}{Sensor\ height\ (mm)} = \frac{object\ height\ on\ sensor\ (pixels)}{Sensor\ height\ (pixels)} \tag{1}$$

$$\frac{object\ height\ on\ sensor\ (mm)}{Focal\ length\ f\ (mm)} = \frac{Real\ object\ size\ (*)}{Distance\ to\ object\ \ d\ (*)} \tag{2}$$

where * denotes real units (feet or meter). A combination of Eq. (1) and (2) is used to obtain the real coordinates (x, y) of wind-borne debris from its flight media.

2.2 Equations of Motion for Wind-Borne Debris in a 2D space

The flight of wind-borne debris is defined by Newton's second law of motion

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} \tag{3}$$

where $\vec{F}$ denotes the force exerted on an object with mass m, $\vec{a}$ denotes the acceleration of the object, and $\vec{v}$ denotes the velocity of the object in space at time t. Two-dimensional motion of a compact (spherical) debris object is considered in this study; the force acting on the flying object is the drag coefficient in a two-dimensional coordinate system (x, y) with the relative wind speed, V_{rel}, acting on the object. These parameters transform Eq. (3) to

$$m\frac{d\overrightarrow{v_x}}{dt} = m\frac{d^2\vec{x}}{dt^2} = 0.5\rho AC_D V_{rel,x}^2 \tag{4}$$

$$m\frac{d\overrightarrow{v_y}}{dt} = m\frac{d^2\vec{y}}{dt^2} = 0.5\rho AC_D V_{rel,y}^2 - mg \tag{5}$$

where A is the projected area of the object normal to the axis of movement; C_D is the drag coefficient of the object, ρ is the air density, g is the gravitational constant (Kaye 2018).

3. CASE STUDY – ANDOVER KS, USA TORNADO (04-29-2022)

A video of the Andover, KS, USA tornado on the 29th of April 2022 was analyzed using the framework from section 2. The sensor height and focal length were taken from the camera metadata, and the distance of the debris object to the observer was estimated using a known path of the tornado and the location of the observer. Three trajectory points of debris A and B were tracked within the tornado vortex, as shown in Fig. 1. The geometry of the debris was assumed to be plate-like, with a drag coefficient of 0.42 and a thickness of 12 mm. The analysis was carried out for debris A and B with an assumed density range of 500 to 1000 kg/m^3, as shown in Tables 1 and 2 below. The result from the analysis shows the estimated value of the velocity of debris (v_debris), the relative velocity of debris to the wind flow (v_rel), and the wind speed (v_wind).

Figure 1. Trajectory of debris object A and B tracked from the Andover, KS, tornado video.

Table 1. Wind speed and debris velocity estimation for debris A.

	Horizontal (x) Component			Vertical (y) Component			Resultant	
Density (kg/m^3)	v_debris (m/s)	v_rel (m/s)	v_wind (m/s)	v_debris (m/s)	v_rel (m/s)	v_wind (m/s)	Debris Velocity (m/s)	Wind Speed (m/s)
500	32	-37	69	17	-23	40	32	79
750	32	-45	77	17	-28	45	32	89
1000	32	-52	84	17	-32	49	32	97

Table 2. Wind speed and debris velocity estimation for debris B.

	Horizontal (x) Component			Vertical (y) Component			Resultant	
Density (kg/m^3)	v_debris (m/s)	v_rel (m/s)	v_wind (m/s)	v_debris (m/s)	v_rel (m/s)	v_wind (m/s)	Debris Velocity (m/s)	Wind Speed (m/s)
500	35	-30	64	13	-24	37	35	74
750	35	-36	71	13	-30	43	35	83
1000	35	-42	76	13	-34	47	35	90

Fig. 2. shows the sensitivity of the estimated wind speed of the flow field to the density, drag coefficient, and thickness of the debris object. The analysis reveals that as the density of the debris object increase, the velocity of the debris becomes a poor proxy for the velocity of the background flow, confirming the need for utilizing the equations of motion to estimate wind speed based on larger debris mass. In addition, the estimated wind speed is sensitive to the aerodynamic drag coefficient of the debris object. Given the difficulties in identifying from video alone the precise geometry of the debris object, and tracking its precise rotation, there is considerable uncertainty in the wind speed estimates.

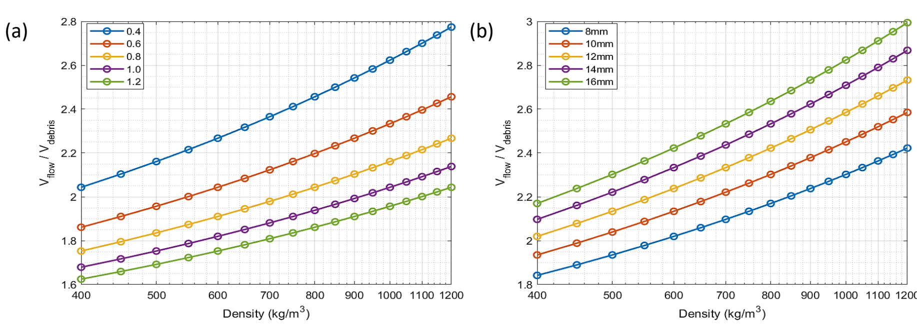

Figure 2. Effect of (a) drag coefficient and (b) debris thickness on the windspeed to debris speed ratio at various densities.

4. EXPERIMENTAL WIND-BORNE DEBRIS TEST BED

Experimental testing will be carried out at the WOW facility to obtain structured debris flight media. The first stage of the experiment will be the calibration of the flow field, and the second stage will be the debris-flight generation and capturing. A preliminary setup of the experiment is shown in Fig. 3, with a base-building model from which debris objects will be released into the wind flow at various wind speeds. The trajectory of the debris objects will be captured using high-resolution cameras, including multiple stereo-imaging pairs, situated at various locations within the experimental footprint. Debris objects will be tagged, and precise landing points captured.

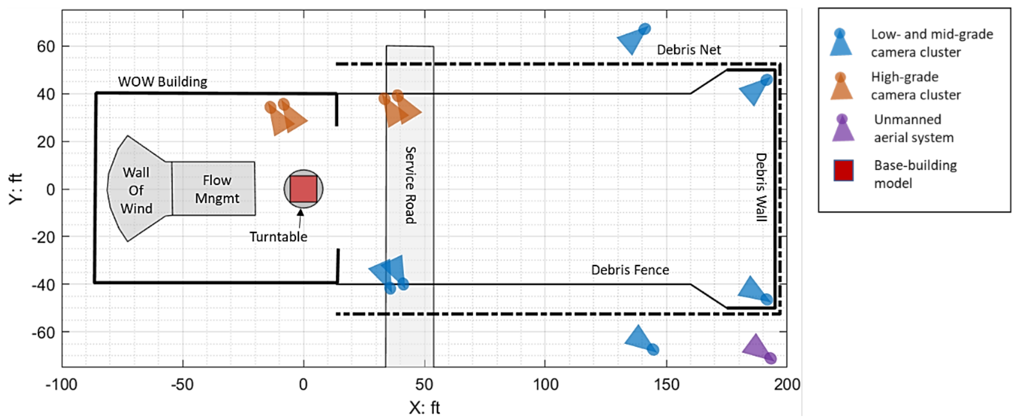

Figure 3. Preliminary placement of cameras in relation to WOW facility and base-building model (debris source).

5. CONCLUSION

This framework demonstrates the possibility of estimating the wind speed at specific points of a flow field by using a physics-based approach to analyze the trajectory of a debris object within the flow field. The comparison of the result using the framework to analyze the Andover, KS, USA tornado with the actual wind speed estimation as an EF 3 tornado can give reasonable estimates, but the estimates are sensitive to assumptions about the debris geometry and mass and need validation from experimental testing. Overall, this framework presents an opportunity to obtain a greater knowledge of near-surface wind and debris characteristics using wind-borne debris trajectory from existing debris flight media.

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