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Experimental analysis of a stochastic model for estimating wind-borne compact debris trajectory in turbulent winds

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ABSTRACT

The impact of flying debris against building envelopes during high winds is a major source of structural damage. For example, damage produced by Hurricanes Katrina and Ike in the United States on the facades of tall buildings, located in urban areas, has been documented. It is therefore of relevance to analyze the vulnerability of tall buildings to debris-induced non-structural damage in the general context of performance-based wind engineering. In order to analyze the random trajectory of debris in highly turbulent winds, a numerical model combined with a probability-based algorithm was recently proposed by the authors (Moghim and Caracoglia, 2013). This model investigates the trajectory of "compact debris", defined as point-mass objects of negligible mass moments of inertia and for which the aerodynamics is predominantly controlled by the drag force. The model replicates both the inherent randomness in debris properties and the effect of wind shear and atmospheric turbulence to estimate debris trajectory and the likelihood of impact against vertical building facades in a probabilistic setting.

This paper describes the comparison between numerical model results and wind tunnel experiments. Tests were carried out in the Northeastern University's small scale wind tunnel in both smooth flow and grid-generated turbulent flow. The motion of spheres and cubes, simulating compact debris objects, was investigated in two dimensions (2D) on a vertical plane.

The 2D motion of compact objects of various sizes was captured by a high-speed digital camera at different flow speeds. Experimental results showed to be consistent with numerical simulations. They also confirmed that not only mean flow speed but also turbulence features can have a non-negligible effect on the trajectory of compact objects.

1. Introduction

Wind-borne flying debris often impact against building facades and envelopes during high-wind events. In the United States, flying objects are usually among the primary sources of wind-induced damage. Some reports and papers, appeared

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after hurricanes Katrina and Ike (Divel et al., 2010) and, more recently, describing the effects of the Joplin Tornado in 2011, have attributed most wind-induced damage to wind-borne debris.

Traditionally, the study of wind-borne debris trajectory has been a concern for special structures such as nuclear power plants and for tornadic winds (Simiu and Cordes, 1976; Twisdale et al., 1979). In recent years, the prediction of the debris trajectory, predominantly in two dimensions (2D), has received significant attention (Lin et al., 2007; Tachikawa, 1983). The study by Wills et al. (2002) proposed a universal three-group classification of wind-borne debris in accordance with their lift-off characteristics and aerodynamic properties: compact, plate-like, and rod-like. Holmes et al. (2006), Baker (2007) and Lin et al. (2006) used this classification and the equations of motions to predict horizontal plate-type object trajectory in a uniform wind field (predominantly 2D). More recently, wind tunnel experiments by Kordi and Kopp (2009) demonstrated that properties such as initial conditions before takeoff (especially velocity) and buoyancy parameter can considerably influence the trajectory of flat plates in uniform winds. These studies also promoted the development of simple empirical equations (Lin et al., 2007), by using experimental results predominantly in 2D, to simplify the prediction of compact debris trajectory and terminal velocity; these equations may become very useful for design. More recently, attention was dedicated to flight in three dimensions (3D) (Noda and Nagao, 2010; Richards et al., 2008).

Despite these significant research efforts a model for trajectory estimation and for prediction of the impact against the envelope of tall buildings is still not available. Also, the hypothesis of uniform wind field has been accepted and used by most researchers to predict debris trajectory. By considering a uniform wind field, wind shear and turbulence effects are either neglected or indirectly simulated (Holmes, 2004) in a simplified way only. Even though it has been suggested that the hypothesis of uniform wind field with constant velocity can be accepted because of the short flight duration (Holmes, 2004), the relevance of the stochastic nature of debris motion in a fully-developed turbulent wind field has been recently noted and investigated, for example to determine minimum initial conditions for takeoff (Karimpour and Kaye, 2012). Most probabilistic models, however, focus on the damage risk assessment in large residential areas for multiple low-rise buildings (Grayson et al., 2012). On the contrary, it is believed that simplified "design curves" (Moghim and Caracoglia, 2012) would possibly be appropriate for the analysis and design of protections and shelters for a single specific tall building.

For compact debris, which is modeled as a point-mass object with the flight being controlled by drag force, the hypothesis of a uniform wind field implies that gravity forces primarily control the object flight and that trajectory mainly depends on the dimensionless Tachikawa number (Tachikawa, 1983, 1988). This dimensionless number is defined as $K = U^2 \rho_{air} A/(2mg)$, with A being a reference projected area of the object and m the mass of the object; ρ_{air} is the airflow density, g the gravity acceleration and U the mean flow speed; it represents the ratio between aerodynamic forces and gravity forces on the object.

Nevertheless, a forensic investigation on the damage caused by Hurricane Wilma in Miami at the top floors of a 26-storey high-rise building identified as compact "debris source" the material on the rooftop of a 9-storey adjacent building (Jain, 2013). This full-scale observation tends to contradict the result that compact debris flight is controlled by gravity and K; it also suggests that careful attention should be considered to apparently unusual debris trajectory paths, for example induced by local flow fields and turbulent wakes.

In order to replicate the upward-trajectory flight in an indirect way, a numerical model, which employs a simulated vertical step-like gust, was proposed by the authors (Moghim and Caracoglia, 2012). This model, although simplified, still cannot fully explain the full-scale observations, for example described by Jain (2013). Therefore, a subsequent investigation, which employs a fully-turbulent wind model for numerical trajectory estimation, was undertaken (Moghim and Caracoglia, 2013). This research showed that, if both wind shear and turbulence are included in the trajectory analysis, their influence on the path of compact objects can be significant.

In this study wind tunnel tests were designed and executed at Northeastern University to analyze and validate the fully-turbulent wind and trajectory model proposed by Moghim and Caracoglia (2013). Tests were conducted in both uniform flow and grid-generated turbulent flow to simulate the main features of atmospheric boundary layer winds (at a wind tunnel scale) and to study the effects of turbulence on trajectories. A rectangular grid, placed upstream of the takeoff position, was used to generate the turbulence features. The trajectory of compact objects of various sizes and shapes (cubes and spheres) was recorded and analyzed using high speed digital videos. The object motion was investigated on a vertical plane at different mean flow speeds.

In the case of smooth flow, wind tunnel trajectories, which were compared to simulation results, showed agreement with maximum relative errors between 5% and 10%. Comparisons were subsequently extended to investigate the effect of turbulence on trajectory and for validating the trajectory model, by using a series of tests in turbulent flow field. The influence of the Tachikawa number on the trajectory of compact debris was also experimentally investigated; the interpretation of the experimental results indicates that cubes tend to fly farther and faster than spheres due to larger drag forces.

2. Description of the wind tunnel experiments

2.1. Wind-tunnel setup

Model experiments were carried out in a closed circuit tunnel, which is operated by a 15-HP 4-pole AC electric motor/fan at a maximum output of 1740 RPMs. A schematic lateral view of the wind tunnel is shown in Fig. 1. The cross section of the