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Effect of computer-generated turbulent wind field on trajectory of compact debris: A probabilistic analysis approach

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ABSTRACT

A model and numerical algorithm is developed to simulate wind-borne debris trajectories in a fully-developed atmospheric boundary layer wind. The model works in two dimensions and makes use of synthetically-generated turbulence time histories; it accounts for variable mean velocity field with elevation and turbulence. The simulation of a partially coherent wind field was based on the wave superposition method (Di Paola, 1998) [1]. For the simulation of the turbulence field, a simplified approach is proposed. First, turbulence is generated at discrete points located on the "inlet boundary" of the field; second, turbulence is propagated through the field using either Taylor's "frozen turbulence" hypothesis or a simplified "Eulerian–Lagrangian" formulation. The latter term is used to emphasize that an expression is employed to approximately replicate the features of the Lagrangian turbulence wind spectrum (for high-speed moving objects), even though turbulence is still synthetically generated on a large portion of the field at all times, from an Eulerian point of view. After generating the wind field, the trajectory of compact objects is estimated by means of a point mass dynamic model, converted to state-space form and integrated by fifth-order Runge–Kutta method.

The numerical model is applied to the study of the risk of impact by wind-borne debris against tall building facades, recently investigated by the authors for uniform non-turbulent wind field only. The analysis is conducted by using the computer-generated wind field to estimate "universal probability curves" (probability-of-impact curves) for compact debris, conditional on the initial distance of the object from the building before takeoff. Both qualitative and quantitative variations are noted in comparison with previous results.

1. Introduction

Flying objects, which are carried by wind in extreme storms such as hurricanes, are classified as wind-borne debris. Damage caused by these objects, which often impact against the façade of buildings, may be significant and can result in relevant repair costs to building envelopes. Impacts should be avoided or minimized [1].

Historically, this topic has been of primary relevance for the design of nuclear power plants due tornado-induced impacts [2,3]. In recent years, this problem has received particular attention and a renewed interest by researchers not only for the study of tornado-induced damages [4] but also because of the destructive effects on the built environment caused by other types of high-wind storms, such as hurricanes or typhoons. Following the pioneering work conducted in Japan a few decades ago on typhoon-generated debris [5,6], more recent studies have been devoted to the categorization of flying objects, based on their aerodynamic properties [7]; others have investigated the estimation of trajectory for each type of object [8,9].

Also in recent years, the structural engineering community has paid attention to the modeling of debris trajectory for risk and performance analysis of residential low-rise construction (e.g., [10]). Damages to tall buildings during high winds have also been recently reported by forensic engineering studies (e.g., [11,12]). A probability-based model for predicting the impact of compact debris against tall building facades has been proposed and investigated by the authors [13,14]. A compact object is classified as a rigid point-mass object with negligible moment of inertia and small projected area (as opposed to large plate-like objects [7]); the aerodynamics is predominantly controlled by drag forces whereas the lift force is negligible.

Needless to say a realistic model for "impact loading" estimation, which accounts for the inherent variability and uncertainty in debris size, mass, flight features and eventually turbulence in the approaching wind field, is not entirely available, in spite of the recent efforts to investigate the stochastic nature of debris motion [15]. As a result, few studies are available on the structural engineering side to analyze (locally) the performance of cladding

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components on the façade [16] or, in general, to promote the performance-based design of cladding elements.

Also, in spite of the fact that several studies have been carried out to estimate the debris trajectory, in most of them the hypothesis of a uniform wind field has been used. This assumption implies that the wind shear and turbulence effects are usually neglected. Even though it has been suggested that the hypothesis of uniform wind field with constant velocity is acceptable due to the limited flight duration [17], the stochastic debris motion in a fully developed turbulent flow field has been recently examined [15]. Also, in a recent study by the writers, it is suggested that the debris momentum at impact against the façade may on occasion be altered, if a simplified vertical gust model is employed for assessing the flight trajectories [14]. Therefore, the simulation of a realistic atmospheric wind field, which includes wind shear and turbulence effects, is of relevance for an accurate analysis of the impacts.

In this study, time histories of computer-generated wind records are used in conjunction with the recently-proposed probabilistic methodology to analyze debris impact against tall building facades. A two-dimensional (2D) wind field model is developed by following two major steps. First, the boundary layer and turbulence time histories are generated at the inlet of the wind field; for validation of these wind time histories, the horizontal and vertical turbulence spectra from the synthetic records are compared to the target spectral model (e.g., Kaimal). Subsequently, the records of the time histories are "propagated", internally to the wind field, without explicitly resolving for wind field at all locations but following two simplified numerical schemes, which will be described in more detail in Section 2. These are employed to overcome the computational burden induced by the need for repeating the generation of wind field scenarios many times in the framework of stochastic trajectory estimation via Monte – Carlo sampling (e.g., [13]).

Once the accurate simulation of the turbulence wind field is established, a series of trajectory examples, including the effects of horizontal and vertical turbulence, are subsequently compared to uniform wind field results. Trajectory results are discussed in relation to the derivation of universal "probability-of-impact" curves, proposed in [13] to assist in the design of cladding elements on the vertical façade of tall buildings. These curves, which are used to describe the probability of impact for a compact object against the façade of a benchmark tall building, have been developed in 2D.

2. Wind field model

2.1. Introduction

The proposed wind field model works in two dimensions and makes use of synthetically-generated turbulence time histories. It accounts for variable mean velocity field with elevation (wind shear effect) and stationary horizontal and vertical turbulence. The simulation of a partially coherent wind field is based on the wave superposition method, developed by Di Paola [1]. The digital simulation uses the principle of superposition of harmonic waves with random phase. This method is briefly discussed in this section.

Time histories of horizontal turbulence, using the Kaimal Spectrum, and vertical turbulence, using the Lumley-Panofsky Spectrum, are digitally generated at equidistant points, equally spaced vertically and horizontally on a 2D grid of a reference 2D region covering the potential debris flight range (Fig. 1). The grid geometry is obtained by discretizing the continuum in the figure. This grid of points is used to estimate the wind field velocity as the object moves into the field.

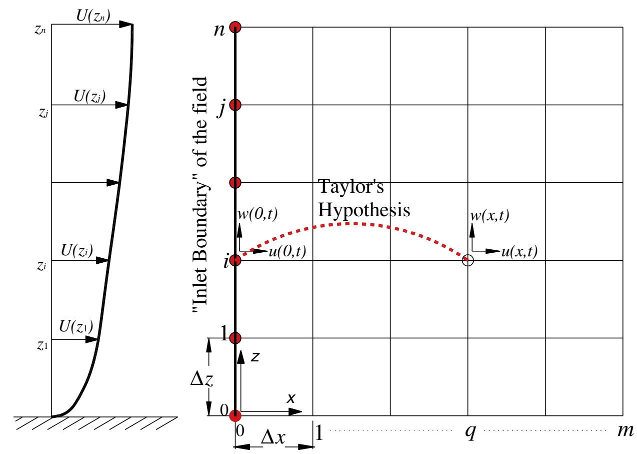

Fig. 1. Discretized two-dimensional grid for digital generation of wind velocity field.

A robust and computationally efficient methodology for wind field generation is needed since the probability-based analysis by Monte-Carlo sampling requires the repeated generation of partially coherent wind fields and the integration of the equations of motion of the object for each of these realizations [13]. In contrast with most applications in wind engineering (e.g., for line-like structures such a tall building or a bridge), the stochastic turbulence field must be simultaneously estimated at several points of the 2D region (Fig. 1). This requirement increases the computational complexity and makes estimation of trajectory by Monte-Carlo methods time consuming. Two simplified approaches are proposed to facilitate the computations; these are described in the next subsections.

2.2. Synthetic generation of boundary layer and turbulence time histories at the inlet of the wind field

As outlined in the previous paragraph, the wind field is built in two steps. First, assuming that the boundary layer mean wind field "flows" from left to right in Fig. 1, the velocity and turbulence characteristics are estimated at discrete points located at the "inlet boundary" of the field on the left side; these are indicated by solid dark (red[1]) markers in Fig. 1 along the vertical line at the horizontal coordinate $x = 0$. The n discrete points at the inlet, where the mean wind velocity and its fluctuations are generated, can be uniquely defined by their vertical coordinates z_i with $i = 1, 2, \ldots, n$ in Fig. 1.

The horizontal wind velocity at each grid point along the inlet ($x = 0$) depends on elevation $z = z_i$; it can be represented as the combination of the mean wind speed and a zero-mean fluctuation, as (in dimensional units)

$$U(x=0,\ z=z_i,\ t) = U_m(z) + u(x=0,\ z,\ t) \tag{1}$$

In Eq. (1) $U(x,z,t)$ is the total horizontal wind speed at a given point of coordinates (x,z) in the 2D region of Fig. 1 and time t; the points have a variable vertical coordinate z but $x = 0$. The term $U_m(z)$ is the mean value of the $U(x,z,t)$, and $u(x,z,t)$ is the horizontal turbulence component. The mean value $U_m(z)$ is derived from the logarithmic law [18]:

$$U_m(z) = \frac{1}{\kappa} u_* \ln\left(\frac{z}{z_{0,r}}\right) \tag{2}$$

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.