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A novel probabilistic approach to assess the blade throw hazard of wind turbines

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ABSTRACT

The increasing number of wind turbine power plant installations and the recent trend to locate them in proximity of build-up areas raise safety concerns as the rotor failure may result in blade throws that can endanger people living/working close to the wind farm. Therefore, it becomes strictly necessary to define setback distances and/or buffer zones to minimize the risk of damage or injury from components failure. However, according to the existing standards, buffer zones and/or setbacks distances are defined by 'rule of thumbs', usually based on the height of the wind tower, and are often overestimated, resulting in too large distances, which may result incompatible with the needs of increasing the number wind power installations. This explains why the scientific community is, now more than in the past, spending a lot of effort in the attempt of developing reliable methodologies able to assess the impact risk in the areas surrounding the wind farm.

In the present paper a very novel and computationally efficient method is presented to estimate the blade throw hazard of wind turbines. The method combines a 3D dynamic model of the detached blade fragment with a rigorous probabilistic approach. Results are shown in terms of safe (white) and unsafe (dark) zones, which are estimated on the basis of an acceptable risk threshold.

1. Introduction

Turbine rotor failures can result in full or partial blade throws. Such events are relatively rare and data describing this kind of failures are relatively scarce. However, rotor failures can produce catastrophic consequences when built-up areas are located close to the wind farm installation. In particular '*blade fragments are documented as traveling over 1300 m*' and '*in Germany, blade pieces have gone through the roofs and walls of nearby buildings*' (see Ref. [3]). Nowadays, because of the constantly increasing number of wind turbine installations and the strong trend to locate wind power plants in proximity of industrial or civil areas, special attention has to be paid to predict blade failures, throw distances and risk of impact. Several factors can cause blade failures [1]: (i) unforeseen environmental events, (ii) incorrect design for ultimate or fatigue loads, (iii) poor manufacturing quality, (iv) failure of turbine control/safety system and (v) human error.

In Ref. [2] two large databases of wind turbines in Denmark and Germany, covering turbine operation in the period 1980–2001, have been analyzed leading to a risk of failures of about 1/4000 per year. A recent report, concerning wind turbine related accidents by Caithness Windfarm Information Forum (CWIF) [3], points out that the number of accidents shows an increasing trend '*with an average of 16 accidents per year from 1995–99 inclusive; 48 accidents per year from 2000–04 inclusive, and 104 accidents per year from 2005–10 inclusive*'. A key point to be considered in the above data is that the highest number of accidents is due to blade failure, which results in full blade or blade fragment thrown. Fig. 1 shows the collected blade failure data per year. We notice that the number of accidents constantly grows as a result of the increasing number of wind turbine installations.

In Ref. [12] the identification of security areas close to wind power plants has been considered necessary only in the case of industrial plants. However this conclusion is not supported by a rigorous statistical analysis. Indeed, the mechanical safety of wind energy turbine is one of the crucial aspects to be considered for their utilization in built-up areas as reported in 'Permitting Wind Energy Facilities' Handbook of the National Wind Coordinating Committee (NWCC) [21], where it is clearly stated that setback requirements must provide an adequate buffer between wind generators and consistent public exposure to minimize the risk of damage or injury from component failures. Setback requirements limit modern wind energy development, resulting in a limited use of large modern power generators (with nominal power exceeding 3.5 MW) because of their very large throw distances. This, in turn,

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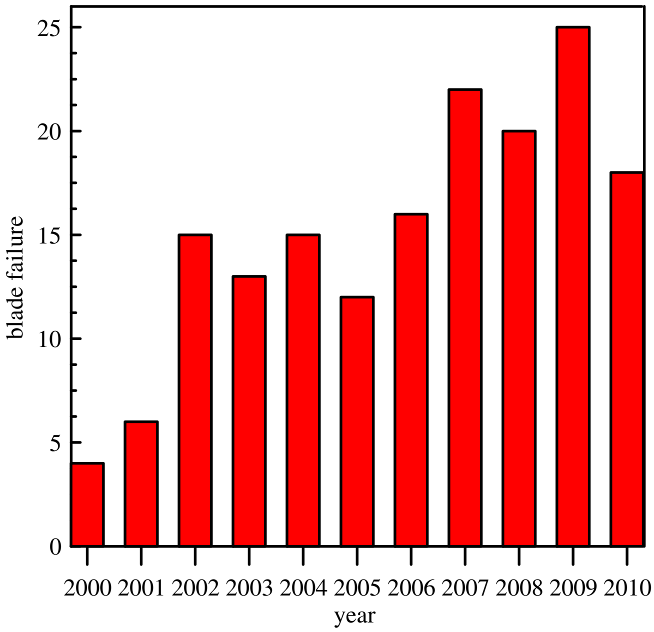

Fig. 1. Number of recorded accidents due to blade failure per years (data from [3]).

lowers the overall wind energy production. In addition buffer zones and setback distances are usually defined, through empirical rules, as a multiple of the total turbine height (generally varying from 1.5 to 3 times the overall machine height), without a real rigorous physical foundation. For example in Ontario the risk of injury is assumed to be minimized with setbacks from 200 to 500 m.

In view of the above arguments, the correct estimation of throw distances of projected blades or their fragments has become of crucial importance to assess the safety of wind power installations. However, the ever stronger boost to exploit wind power plants as one of the most promising green energy sources, is pushing the safety analysis well beyond the determination of throw distances. Recently the scientific community is attempting to develop sophisticated methodologies to estimate the probability density distribution of impacts in the areas surrounding wind turbines. Summarizing the present state of art, we recall that most of the studies deal with the development of dynamic models describing the in-flight motion of blade fragments, subjected to gravity and aerodynamic forces, in order to determine the throw ranges and impact probability distribution under different running conditions [4–8,13]. However these are usually based on simplified assumptions: (i) the blade fragment is considered as a point mass subjected to a constant aerodynamic drag [4,6], (ii) the probability distribution of wind directions is simply uniform, (iii) results are obtained for a very coarsely discretized surrounding area, in sectors or ring zones [4,5,8], which may be not enough to correctly characterize the impact risk level point by point around the wind turbine. The point mass assumption and the constant aerodynamic drag hypothesis were removed in some studies [5,7,13,15], where a full 6-DOF model of the blade fragment was considered, and the aerodynamic forces were determined by: (i) splitting the fragment into segments, (ii) calculating the aerodynamic forces and moments on each segment and (iii) summing up the contribution of all segments. Incidentally, we observe, that a similar approach is used in current state-of-the-art modeling of wind turbine rotors in the industry. Monte Carlo simulations were proposed in Refs. [9,10] to derive a probability distribution of fragment impact points with a defined confidence level. In this respect, an alternative procedure was proposed in Ref. [14] based on the analysis of historical data. This approach was exploited to predict the reliability of large wind turbines. In Ref. [11], the probability distribution of blade fragment throws was also determined assuming equal weighting for all wind directions. More recently, Slegers et al. [15] by coupling a 6-DOF dynamic model of the blade with Monte Carlo simulations calculated the probability of a blade fragment impacting an electric-power transmission line. A similar approach was used in Ref. [16] to define setback standards. However analyses based on tens of thousands of Monte Carlo simulations are extremely expensive from the computational point of view and may prevent an easy, fast and economically convenient risk assessment of wind turbines installations.

In the present paper we develop a novel, rigorous and computationally efficient probabilistic approach to estimate the blade throw hazard of wind turbines. The method takes as input data: (i) the loci of the impacting points of the projected blade fragments in a reference frame fixed to the nacelle of the wind turbine for any given wind intensity, and (ii) the joint probability distribution of wind intensity and wind direction. The locus of the impacting points is determined on the basis of a full 6-DOF dynamic model of the blade fragment which has been developed on the line already traced by other existing works as those by Sørensen [7] or Rogers et al. [16]. The 6-DOF is only very briefly summarized, whereas the probabilistic calculations, constituting the real novelty of this paper, is described in great detail. Results are presented in terms of safe (white) and unsafe (black) zones, given a certain acceptable risk threshold.

2. Brief description of the 6-DOF dynamic model of the projected blade fragment

To determine the motion of a blade fragment in air, one of the key input data is the angular velocity ω_R of the wind turbine rotor. However, given the wind speed V, this quantity is known because the controller uniquely determines it, depending on V, in order to maximize the electric-power generation ([17–20]). Therefore, given the wind speed V and the altitude angle β of the blade at which detachment occurs (see Fig. 2), the detached blade fragment of length L will impact the ground in a certain area surrounding the point $\mathbf{P}(R,\Theta)$ where $R(\beta,L,V)$ and $\Theta(\beta,L,V)$ are, respectively, the distance of $\mathbf{P}$ from the vertical axis of the wind turbine tower, and its azimuthal position measured counterclockwise from the rotor plane (see Fig. 3). By changing the altitude angle β, given the wind intensity V, the point $\mathbf{P}$ describes the locus Γ schematically shown in Fig. 3. It is worth noticing that, in the reference frame $\Lambda \equiv (\mathbf{O}xyz)$ fixed to the nacelle, the locus Γ is independent of the wind direction α but only depends on V. In fact, the nacelle rotates about the tower axis so to align its axis with the wind direction.

In order to calculate the functions $R(\beta,L,V)$ and $\Theta(\beta,L,V)$, and, hence the locus Γ of impact points, it is necessary to calculate the trajectories and the throw distances of the detached blade fragment. To this end we need to solve the governing equations of the motion of the blade fragment. This problem has been efficiently solved in many works [6,7,13,15,16]. Here we only provide a brief description of the method we have adopted to solve the dynamic problem. Our method is very similar to the one proposed in Ref. [15], it does not include unsteady effect as dynamic stall, dynamic wake/inflow or phenomena as autorotation and others which may have a non-negligible influence on the flight dynamics of the blade fragment [7]. However, we stress that the focus of our investigation is on the methodology to calculate the risk of impact of a blade fragment and in particular on the probabilistic approach to obtain such a result. Indeed, the same probabilistic approach can be usefully exploited also in conjunction with much more complicated blade flight models which may be present in literature