SHORT COMMUNICATION

Mapping hail meteorological observations for prediction of erosion in wind turbines

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ABSTRACT

Wind turbines can be subject to a wide range of environmental conditions during a life span that could conceivably extend beyond 20 years. Hailstone impact is thought to be a key factor in the leading edge erosion and damage of the composite materials of wind turbine blades. Using UK meteorological data, this paper demonstrates that the rotational speed is a crucial factor in determining the magnitude of the kinetic energy associated with singular impact and is likely to be significant for incidents of hail. An improved representation of hail characteristics, occurrence probabilities and realistic impact component velocities is also proposed, from which the prospect of individual impact by large hailstones is found to be very scarce. Instead, the damage posed by multiple impacts throughout wind turbine operation is assessed. The annual average cumulative impact energy for a high frequency of hail case study is determined and evaluated against example composite failure threshold energies in the literature. © 2015 The Authors. Wind Energy published by John Wiley & Sons Ltd.

KEYWORDS
wind turbines; hail; erosion; meteorology

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1. INTRODUCTION

In order to harness energy from the wind, wind turbines are installed at a diverse range of geographical regions across the world. Depending on the location, individual turbines can be subject to a multitude of hazardous and hostile environmental conditions over a proposed 20+ year life span. The International Electrotechnical Commission recognizes a number of different environmental parameters that are instrumental in turbine design and durability, including the effects of hail.1 Hail is also considered by various providers of protection measures as one of the key particles associated with the erosion of wind turbine blade composite materials.

The erosion process typically starts at the leading edge of the blade, where the first visual signs of damages are pits in the paints/coatings that gradually increase in density to form gouges. This continues towards the blade root and on the upper and lower surfaces of the aerofoil. The degradation of the coatings near the tip eventually results in delamination initiating at the leading edge and, in extreme cases, is further propagated to and through the resins and fibres. A deterioration in blade surface condition due to erosion can lead to a substantial increase in drag along with a decrease in lift coefficient, resulting in a significant reduction in annual energy production.2

Many experimental investigations in the literature regarding hailstone impact3–5 have discussed the effects of hail with respect to aerospace structures. Although there are few examples of research specific to wind turbines, the issue of hail impact on wind turbines has been explored by Keegan et al.6,7 Here, the hailstone impact velocity is characterized by three component velocities; the terminal velocity of the hailstone, the mean wind speed and the wind turbine tip speed. One example discussed by Keegan et al. is a 15 or 30 mm diameter hailstone entrained in a 20 m s⁻¹ horizontal wind striking a blade tip, with 90 m s⁻¹ tip speed.
As a precursor to performing detailed modelling of hail impact events specific to wind turbines, it is important to understand the likelihood of those scenarios. In addition to the aforementioned constituent velocities, the extent of erosion is influenced by the material properties of both the particle and the target, particle size and number and the angle of impingement. By analysing UK meteorological data, this paper intends to formulate a realistic representation of these influences. In order to relate potential hail risks to practical cases and inform future erosion model development, the location of UK wind farms relative to prevalent hail stations will be considered and a range of plausible incidents developed for specific turbine cases.

2. METEOROLOGICAL DATA

Meteorological data were provided by the British Atmospheric Data Centre, consisting of three separate datasets: Met Office Integrated Data Archive System (MIDAS) land and marine surface stations,9 the Chilbolton Facility for Atmospheric and Radio Research (CFARR)10 and the Natural Environment Research Council (NERC) Mesosphere–Stratosphere–Troposphere (MST) Radar Facility at Aberystwyth.11 The renewable energy planning database extract published by the Department of Energy and Climate Change was also used to determine wind farm locations in operation, as well as those awaiting or under construction.12 This information was detailed up to September 2014 and was filtered to only include farms greater than 1 MW capacity.

The MIDAS dataset includes a range of daily weather values taken from land surface measurement stations in the UK. At a range of stations, a description of a ‘hail day’ is recorded and categorized by World Meteorological Organization codes that range from 1 (diamond dust) to 7 (hail) (diameter 20 mm or more). At the majority of these stations, mean wind speed is also measured. The data interval was taken from the start of 1949 to the end of 2013.

The facility at Chilbolton has a variety of instruments used to measure precipitation. On the 12th of December 2011, a Campbell Scientific PWS100 (Campbell Scientific, Loughborough, UK) weather sensor was installed at the site. This laser-based instrument is capable of determining different varieties of precipitation by analysing size and velocity measurement signals. Included in the distinct classifications are hail and graupel (snow pellets). The measurements were taken at intervals of 1 min up to the 31st of October 2014.

The NERC MST dataset utilizes a Vaisala Weather Transmitter WXT510 (Vaisala, Vantaa, Finland), which measures a variety of surface meteorological parameters in three independent measurement cycles. Precipitation is measured by a piezoelectric sensor that has an area of 60 cm². Hail accumulation and rate are measured at 10 s intervals. Internal signal processing is used to differentiate between the signals generated by rain, hail and undesired sources. The data interval available was from the 21st of December 2007 to the 31st of October 2014, but up to 2013 measurement for each year was restricted to periods between October and December.

3. RESULTS

3.1. Prevalence of hail in the UK

In order for hailstones to form in convective storms, the temperature has to be close to water freezing levels. Consequently, hailstone occurrences at MIDAS stations in the UK are highly seasonal, as demonstrated in Figure 1. The percentage of stations reporting a ‘hail day’ is severely diminished over the summer months for all the years of data. The winter and

![Figure 1. Percentage of UK MIDAS stations reporting a ‘hail day’ (1949–2013).]
spring periods see increased hail activity, where the temperature in the upper atmosphere is sufficiently cool to develop ice formation but warm enough on the surface to encourage thunderstorm development. The figure also appears to show a reduction in reported hail days over the decades, indicating a change in weather patterns. However, this may be influenced by the change in the number of operating hail recording stations, for which significant increases were observed in 1959, 1971 and 1994. Since 1994, the number of these stations has been in steady decline.

By analysing the number and type of ‘hail days’ across the UK from MIDAS meteorological data, an impression of hail occurrence was formulated. Firstly, a distribution of the different hail types was created for the time frame studied, as displayed in Figure 2. Inspection of the distribution shows that ice pellets/small hail (\( \phi < 5 \) mm) is evidently the most frequent category, with hail (5 mm \( \leq \phi \leq 9 \) mm) the next ranked. Conversely, the largest hail category, hail (\( \phi \geq 20 \) mm), has the lowest frequency of all the classifications, with hail (10 mm \( \leq \phi \leq 19 \) mm) also considerably low in occurrence. Snow pellets/graupel, snow grains and diamond dust make up the remaining rankings of third, fourth and fifth, respectively.

Although hailstorms and extreme hail sizes in the UK are not as prevalent as certain countries with large numbers of wind turbine installations, the probability density of hail diameters is comparable.14

The annual number of hail days at each MIDAS station per year is displayed in Figure 3. Wind farm locations are also presented and scaled according to total wind farm capacity. The stations that endure the most hail annually are found mainly in the west and north-east of Scotland, as well as Orkney and Shetland. Noticeably, these stations are typically situated near the coast or on islands. There are also clusters of higher frequency stations located in the southwest of England and Wales, with stations experiencing no hail spread out across the UK. Although the most frequent hail locations do not coincide with the regions where wind farm density is greatest, there are specific examples of proximity across the UK.

Figure 4(a) displays the breakdown of hail experienced at those MIDAS stations separated by a 1 km distance from the coastline. Many of the stations that receive the greatest amount of hail (hail days > 30) are situated closer to the coast. The mean number of hail days per year for these coastal stations is \( \sim 10.5 \) compared with \( \sim 6.5 \) for those more inland. By increasing the threshold to 5 km, a greater portion of the frequent stations are captured, as shown in Figure 4(b). Approximately 2.26% of all MIDAS stations receive more than 30 days of hail per year on average. However, the trend for all cases that indicate lower occurrences is more commonplace, with the majority of stations subject to 0 < hail days \( \leq 5 \) per year on average.
Collating all the distributions from the MIDAS stations, an average impact profile for each category of hail can be produced, as shown in Figure 5(a). Standard deviations for each category are also included. The profile follows a similar rank to that of Figure 2, with categories ‘d’ and ‘e’ determined to have the greatest mean hail days per year of 3.91 and 2.5, respectively. Category ‘c’ is found to have less than a day a year on average, but this would scale to the number of operational years of the turbine. Categories ‘a’ and ‘b’ experience even less than this and are unlikely to be considered for damage modelling because of their size and composition. The mean occurrence for the larger sizes of hail would represent a one-off unique event in the lifetime of a wind turbine for such a profile in the UK.

To offer a higher frequency case study, the distribution profile of MIDAS station that experienced the highest average number of annual hail days can be used to simulate the upper range number of incidents, as displayed in Figure 5(b). The number of incidents per year for categories ‘c’, ‘d’ and ‘e’ at this station is considerably more than those shown in Figure 5(a). A wind farm situated close to the MIDAS station experiencing the most number of hail days per year should provide a corresponding impact profile.

### 3.2. Hailstorm durations

Because of the insufficient resolution provided by the number of days of hail, data from the CFARR and NERC stations was also analysed. Table I describes the duration of both continuous and non-continuous (interrupted periods within 24 h of a hail event) hailstorms. Continuous hail is found to last a matter of minutes, whereas non-continuous instances of hail can last significantly longer. Different types of hail are not mutually exclusive, with incidents of graupel and hail occurring during the same intervals at the CFARR observatory. It should be noted that the number of hail days at both facilities is greater than their nearest MIDAS station counterparts, which record less than a day of hail a year on average. This observation is magnified at the NERC facility where measurements are only taken between October and December and hence miss some periods of peak hail, as demonstrated in Figure 1. The mean rate of hail measured at the NERC facility ranges from 1 to 21 hits cm$^{-2}$ h$^{-1}$, with lower rates occurring far more regularly.
Table I. Duration of hailstorms at CFARR and NERC observatory stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Resolution</th>
<th>Number of ‘Hail Days’</th>
<th>Continuous duration</th>
<th>Non-continuous duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per year</td>
<td>Mean (min)</td>
<td>Maximum (min)</td>
<td>Mean (h)</td>
</tr>
<tr>
<td>CFARR (hail)</td>
<td>1 min</td>
<td>11.66</td>
<td>1.79</td>
<td>10</td>
</tr>
<tr>
<td>CFARR (graupel)</td>
<td>4.46</td>
<td>2.2</td>
<td>10</td>
<td>3.82</td>
</tr>
<tr>
<td>NERC MST</td>
<td>10 s</td>
<td>12</td>
<td>1.19</td>
<td>3.33</td>
</tr>
</tbody>
</table>

Table II. Summary of fall-speed relations for a range of hail ($H$) and graupel ($G$) diameters ($D$), adapted from Dawson et al.$^{17}$

<table>
<thead>
<tr>
<th>Author</th>
<th>Category</th>
<th>Fall-speed relation</th>
<th>$a_H$ or $a_G$</th>
<th>$b_H$ or $b_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wisner et al.$^{15}$</td>
<td>Hail</td>
<td>$v_{H} = y a_H D_H^{b_H}$</td>
<td>$\frac{4 \rho_G - \rho_H}{3 \rho_H} C_d = 0.8$</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Graupel</td>
<td>$v_{G} = y a_G D_G^{b_G}$</td>
<td>$\frac{4 \rho_G - \rho_H}{3 \rho_H} C_d = 0.45$</td>
<td>0.37</td>
</tr>
<tr>
<td>Ferrier$^{16}$</td>
<td>Hail</td>
<td>$v_{H} = y a_H D_H^{b_H}$</td>
<td>19.3</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Graupel</td>
<td>$v_{G} = y a_G D_G^{b_G}$</td>
<td>206.984</td>
<td>0.6384</td>
</tr>
</tbody>
</table>

$C_d$ represents the coefficient of drag, $\rho_G$ and $\rho_H$ are the particle densities and $g$ is the gravitational constant.

Figure 6. Nominal tip speeds and diameters for wind turbines $\geq 1$ MW. Empty markers represent turbines still in the prototype stage or awaiting certification.

3.3. Velocity components

In this section, the likelihoods of the component impact velocities are evaluated. These include the terminal velocity of the hailstone, mean wind speed and the rotational speed of the wind turbine. The terminal velocity can be estimated using separate empirical formulae derived from Wisner$^{15}$ and Ferrier$^{16}$ as displayed in Table II. Both sets of formulae depend on the density correction factor $\gamma = \left( \frac{\rho_H}{\rho_A} \right)^{0.5}$ (where $\rho_A = 1.204$ kg m$^{-3}$ and $\rho_A$ is the air density), the particle diameter ($D$), a further parameter $a$ and an exponent $b$. Considering the most common category of ice pellets/small hail ($\sigma < 5$ mm) and assuming a worst-case density of $\rho_H = 900$ kg m$^{-3}$, the terminal velocities for a larger diameter of 5 mm are calculated to be 9.315 (Wisner) and 6.646 m s$^{-1}$ (Ferrier). For a diameter of 10 mm, this is determined to be 13.17 and 10.35 m s$^{-1}$.

The nominal tip speeds of wind turbines greater than 1 MW are displayed in Figure 6. Assuming that the majority of wind turbines have a cutout wind speed of around 25 m s$^{-1}$, it is proposed that despite the range of design preferences, the rotational speed is the most important factor in defining the severity of the impact velocity. Reexamining the example of Keegan discussed in Section 1 for a 5 mm hailstone, the tip speed component constitutes between 88.8% and 95.2% of the overall resultant impact velocity.

Although the mean wind speed may not directly contribute as much to the magnitude of the impact velocity, it will inform the rotational speed of most modern variable speed wind turbines. Below rated wind speed, usually in the range of
11–16 m s$^{-1}$, the rotor speed is varied with wind speed to maintain peak aerodynamic efficiency. At and above rated wind speed, the rotational speed conforms to a nominal value. Figure 7(a) describes daily mean speed distributions taken from stations that experience a certain range of hail days per year, with Figure 7(b) describing the average mean wind speeds for those stations. The figure indicates that those stations which are subject to more hail days show a broader wind portfolio and overall higher mean wind speeds. Increased probability of wind speed around the rated wind speed range is especially evident for stations enduring 20 days or more of hail.

### 3.4. Case study

Combining all the analysis of prevalence, duration and the velocity components of hail impact in the UK, the likelihood of annual hail damage through erosion can be estimated. Assuming nominal operation of the turbine and utilizing the Wisner et al.$^{15}$ fall-speed relation and associated parameters (Table II), the kinetic energy for different sizes of hail can be calculated. These are obtained using the formula $T_1 = \frac{1}{2}mv_0^2$, where $m$ is the mass of the hail particle and $v_0$ is the initial impact velocity. Different values of kinetic energy just before impact can be observed for discrete locations along the blade in Figure 8.

For the high frequency case displayed in Figure 5(b), the annual average cumulative energy for blade tip impacts by each hail category was calculated. Diamond dust and snow grains were excluded from considerations. Assuming one impact per hail event and the upper diameter threshold for each category, ‘Ice pellets/small hail ($\varnothing < 5$ mm)’ contributed the most to the overall cumulative energy with approximately 7.55 J, compared with the least from lower density ‘snow grains/graupel’ (~ 1.13) J. Despite experiencing differing numbers of hail days, ‘hail (5 mm $\leq \varnothing < 9$ mm)’ and ‘hail 10 mm $\leq \varnothing < 19$ mm’ had similar cumulative values of around 4.94 and 5.5 J, respectively. By aggregating the separate contributions, the total impact energy was found to be roughly 19.11 J. This is notably less than the cumulative failure threshold energy of 72–140 J revealed by Appleby–Thomas et al.$^5$ for carbon fibre-reinforced polymers or even the higher values for glancing impact disclosed by Kim et al.$^4$.

![Figure 7. Daily mean wind speeds at MIDAS stations subject to a discrete range of hail days on average per year.](image1.png)

![Figure 8. Kinetic energy of different diameters of hailstone for impact at certain radial positions of a wind turbine blade.](image2.png)
4. CONCLUSION

From the meteorological data investigated, ice pellets/small hail (diameter < 5 mm) is the most frequent category of hail experienced by MIDAS stations. Incidents involving diameters of hailstones greater than 20 mm are very rare events, with only 102 incidents recorded over the entire 65 year period. The majority of stations experience fewer than 5 days of hail a year, with an average incident profile per year developed in Figure 5(a). The stations that endure more hail are found mainly in the north and west of Scotland. These stations do not correlate with the areas where wind farms are most prominent but there are individual examples.

The contribution of the tip speed to the overall impact velocity is highlighted. The wind speed is found to be greater at stations experiencing more frequent hail days, which indicates that rated operation of wind turbines will be more likely at these stations. As well as directly influencing the rotational speed, the wind speed will also inform the pitching of the blades. As impact angle is an important variable in erosion of materials, a range of impact angles on the turbine blade should be considered.

For a study with a high frequency of hail, the average annual cumulative impact energy was found to be approximately 19 J at the blade tip. For this exceptional case, the early signs of damage would not be expected until a wind turbine blade, composed of carbon fibre-reinforced polymer, has experienced multiple years of impact. The implications for blades constructed using glass fibre should also be investigated. These observations will be assessed by future experimental and computational analysis.

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