A computational model of wind turbine blade erosion induced by raindrop impact

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Abstract. This research focuses on developing a computational model for analysing wind turbine blade erosion induced by raindrop impact. A stochastic rain texture model is used to simulate realistic rain events determined by a rain intensity and a rain duration. A new smoothed particle hydrodynamic approach is implemented to study the influence of the raindrop size, impact speed, impact angle, and raindrop shape on the impact stress. In addition, a stress interpolation method is proposed to accurately and efficiently calculate the impact stress under a random rain event. The fatigue damage of the top coating material is evaluated under a rain event based on the rainflow cycle counting method and the Miner’s rule.

1. Introduction
Blade damage induced by impacts of high-relative-speed objects, such as rain, atmospheric particles, hail, and sand is becoming increasingly important as wind turbines continue to grow in both hub-height and rotor diameter. Among these objects, raindrop impact is one of the most important factors significantly influencing the fatigue life \([1-2]\) and degrading aerodynamic performance \([3-5]\) of wind turbine blades. This research presents a computational model for analysing the wind turbine blade erosion induced by raindrop impact.

For the rain erosion problem, there are two different types of approaches, the impact approach (e.g. \([6]\)) or the energetic approach (e.g., \([7]\)). The former approach first calculates the impact pressure using either explicit formula, e.g., the water-hammer equations \([8-9]\), or the expensive computational fluid dynamic (CFD) methods (e.g. \([10]\)), then carries out the transient stress analysis by applying the pressure force on the finite element model of a wind turbine blade (e.g., \([10]\)). Although it is computational cheap to calculate pressure by the explicit water-hammer equations, three assumptions are made: (1) the impact occurs in one dimension, (2) the impact solid is a perfect rigid body, and (3) the speed of sound and density are constant \([8]\), which do not realistically represent raindrop impacts. In addition, it is difficult
to take into the account the fluid-solid interaction during raindrop impact by sequentially calculating the impact pressure and the transient stress. The energetic approach attempts to relate the erosion to mechanical properties of the impact body based on the kinetic energy transmitted. Although this approach can potentially avoid simplifications (e.g., the impact effects are independent of each raindrop and the shape of raindrops is a perfect sphere), it is difficult to quantify the total transferred energy from the stochastic rain field to the wind turbine blade.

Considering a realistic rain event, this paper first presents a stochastic rain field simulation conducted for a given rain intensity and rain duration. The smoothed particle hydrodynamic (SPH) method is used to study the interaction between raindrops and the impacted blade, and to efficiently calculate the raindrop impact stress on both the top coating and the inner composite material of a wind turbine blade. To reflect the diversity of raindrops in a rain event, the SPH analyses are investigated considering different raindrop sizes, impact speeds, impact angles, and raindrop shapes. The compounded stress due to multiple raindrops impact in a simulated rain field is calculated based on interpolation of stress results of single raindrop impact by the SPH method. Using the obtained raindrop-impact stress, fatigue damage of the blade is calculated incorporating the stochastic rain field, the SPH analysis, and the non-proportional multi-axial complex stress states.

2. Stochastic rain field simulation

A high-fidelity simulation of a rain event is important for accurately predicting the erosion process. However, being complex natural phenomena it is challenging to simulate realistic rain events due to varied raindrop sizes, shapes, and velocities. For example, the raindrop size that is not homogeneous during the rainfall follows a continuous distribution indicating the number of raindrops with a specific diameter in a unit volume of air [11]. Different raindrop shapes exist, e.g., spherical, semi-oblate, and parachute forms for raindrops diameter less than 2 mm, between 2 and 5 mm, and larger than 5 mm, respectively [1]. Additionally, the shape of raindrops is highly dynamic in response to e.g. coalescence or fragmentation. Moreover, the terminal velocity, i.e., the highest velocity attainable by the raindrop falling through the air, is affected by the raindrop mass, humidity, temperature, and orography, as well as the wind. Thus, it is a challenging task to simulate a realistic stochastic rain field considering all the aforementioned factors. In this paper the rain is considered as a Poisson process that exhibits complete spatial randomness. However, the effect of raindrops coalescence or fragmentation during falling are not yet taken into account [12].

With the above assumption, we adopt the compounded stochastic rain texture model proposed in [10] for the stochastic rain field simulation. The simulated stochastic rain field consists of three key components including the number of raindrops in unit volume, the distribution of the size of raindrops, and the spatial distribution of raindrops in the simulated volume. The number of raindrops in unit volume \( V, N(V) \), follows a Poisson distribution expressed as:

\[
P(N(V) = k) = \frac{(\lambda V)^k e^{-\lambda V}}{k!}
\]

where \( \lambda \) is the expected number of raindrops per unit volume and \( P(N(V) = k) \) is the probably of finding \( k \) raindrops in volume \( V \). Based on the relationship between the volume of water in air and the rain intensity suggested by Best [11], the expected number \( \lambda \) of raindrops per unit volume can be derived by a power law relationship with the rain intensity as follows [10]:

\[
\lambda = 48.88 I^{0.15}
\]

where \( I \) is the rain intensity in mm/h. To relate the rain intensity with the distribution of the size of raindrops, Best’s drop size distribution is used since it’s closely matches the experimental data [11]. It’s cumulative distribution function (CDF) \( F \) is expressed as:

\[
F = 1 - \exp \left[-\left(\frac{d}{1.3 I^{0.232}}\right)^{2.25}\right]
\]

where \( d \) is the drop diameter in mm.
Considering the tip speeds of modern large wind turbine blades and raindrop terminal speed, a feasible impact speed could be 90-100 ms\(^{-1}\) [13]. Since the wind turbine blade tip speed is significantly larger than the rain falling speed, in this paper the raindrops are considered as motionless and uniformly distributed in a tall column with a base area of the blade impact panel (100 × 100 mm). The height \(h\) of the column is calculated by the multiplication of the impact speed (100 ms\(^{-1}\)) and the duration \(T\) of the simulated rain event. Figure 1 shows the cross-sectional views of simulated stochastic rain fields with varied-size spherical raindrops under four rain intensities (1 mm/h, 10 mm/h, 50 mm/h, and 100 mm/h).

![Figure 1. Simulated stochastic rain fields under four rain intensities: (a) 1 mm/h, (b) 10 mm/h, (c) 50 mm/h, and (d) 100 mm/h.](image)

### 3. Smoothed particle hydrodynamic analysis of raindrop impact

In this section, the raindrop impact process is simulated by the transient smoothed particle hydrodynamics (SPH) using a finite element analysis (FEA) model in ABAQUS/Explicit. This SPH approach has three merits: (1) taking into account of large deformation of raindrops during impact on
the solid, (2) directly calculating the transient stress time series and (3) characterizing the impact wave propagation in the FEA model. Detailed explanation of this approach is elaborated as follows.

3.1. Impact stress calculation via SPH considering single raindrop

The layup of the FEA model consists of a top coating, a composite layer beneath the coating layer, a foam layer in the middle, and another composite layer at the bottom (Fig. 2). Since the wind turbine blade tip speed is significantly large, raindrop erosion at the tip of the blade is more serious than other parts. This paper analyzes the panels at the tip of the blade. The coating material is referred from the gelcoat used in the Sandia 100-meter all-glass baseline wind turbine blade [14]. The two composite layers are both made of composite materials QQ1, which is a glass-fiber-reinforced plastic (GFRP) laminate that consists of Vantico TDT 177-155 Epoxy Resin, Saertex U14EU920-00940-T1300-100000 0’s, and VU-90079-00830-01270-000000 45’s fabrics [15]. The form core material is selected to be Corecell™ M-Foam M200 [16]. Detailed material properties are provided in Table 1. The dimension of the blade panel is 100 × 100 × 15.6 mm. The boundary condition is set to fixing the bottom surface of the panel as a typical approach for raindrop impact simulation (e.g., [17]). Due to the consideration of cohesive property between layers, the stress analysis calculation will be complicated. To simplify the calculation we make a assumption that the layers in the sandwich panel are considered to be perfectly bonded. There are 10000, 100000, and 50000 SC8R elements used to mesh the coating layer, the two QQ1 layers, and the foam layer, respectively.

| Material Properties | Material Types | Coating | QQ1     | Foam   |
|---------------------|----------------|---------|---------|--------|
| Longitudinal Young’s modulus $E_1$ (GPa) | 3.44 | 33.1     | 0.256   |
| Transversal Young’s modulus $E_2$ (GPa) | 3.44 | 17.1     | 0.256   |
| Poisson’s ratio $\nu_{12}$ | 0.3  | 0.27     | 0.33    |
| Shear modulus $G_{12}$ (GPa) | 1.38 | 6.29     | 0.098   |
| Density $\rho$ (kg/m$^3$) | 1235 | 1919     | 200     |

Figure 2. Simulation of one raindrop impacting on a panel of a wind turbine blade.
SPH is a Lagrangian modeling method permitting the discretization of a prescribed set of continuum equations by interpolating the properties directly at a discrete set of points (or particles) distributed over the solution domain with the need to define a spatial mesh. It uses an evolving interpolation scheme to approximate a field variable at any point in a domain. The variable value at a particle of interest can be approximated by summing the contributions from a set of neighboring particles, denoted by subscript $j$, for which the kernel function, $W$, is not zero, expressed as,

$$f(x) = \sum_j \frac{m_j}{\rho_j} f_j \left( \left| x - x_j \right|, h \right)$$

where $m_j$ is mass of particle $j$ in kg, $\rho_j$ is density of particle $j$ in kg/m$^3$, $f_j$ is the value of the quantity $f$ for particle $j$, $x$ is the position of the particle of interest, $x_j$ is the position of particle $j$, $h$ often called smoothing length, is a measure of the support of $W$.

The SPH approach is particularly effective to solve large deformation problems that can afford moderate computational cost, which is its key advantage over traditional FEA and the coupled Eulerian-Lagrangian approaches. The former is not accurate for large deformation analysis, while the latter is usually more computationally expensive than SPH. Detailed theory and application of SPH could be found in literature, e.g., [18-20].

Figure 3 demonstrates the propagation of von Mises stress of the panel under a single spherical raindrop normal impacting at the panel center. The raindrop diameter is 2 mm and the impact speed is 100 ms$^{-1}$. As a result of the impact, Figs. 3(a-f) clearly show that a Rayleigh wave is generated and propagated from the impact center to free boundary at the surface coating. In addition, the impact
produces longitudinal and transverse body waves which accompany with stress variation inside the panel exhibiting an interference field of these waves (Figs. 3(g-l)). Two high stress regions are observed during the raindrop impact process: the one occurring at the raindrop-coating contact surface (Figs. 3(b-f)) and the other is propagating through the thickness below the surface (Figs. 3(g-l)). The former is due to the raindrop peak impact pressure acting as the primary wave source, while the latter is caused by the superposition of stress initiated from the shock wave front in the raindrop and high pressure point [21]. These findings further confirmed that micro-crack/fatigue is possibly occurring both at the raindrop-coating contact surface and underneath the coating. It is worth noting that there is a clear stress interface between the QQ1 layer and the foam layer (Figs. 3(h-l)) due to different elastic material properties of the two layers. In the assumption of perfectly bonded layers, the elastic deformation of QQ1 and foam layer is the same in the interfaces between layers. The Young's modulus of foam layer is much lower than that of QQ1 layer, so foam layer stress is much lower than QQ1 layer. This finding confirms that the foam layer plays an important role as a stress cushion in composite wind turbine blades.

The influence of the raindrop size, impact speed, impact angle, and raindrop shape on the stress evolution on the impacted coating is investigated as demonstrated in Fig. 4. Due the significantly large stress observed at the center of the top coating, the von Mises stress extracted from the element at the center of the top coating layer is studied. Figure 4(a) shows the von Mises stress induced by the normal impact (90º) under the same impact speed (100 ms$^{-1}$) and different raindrop diameters (1 mm, 2 mm, and 5 mm). A clear two-peak mode is observed for the stress time series of all three cases and the gap between the two peaks is increased as the raindrop size increases (Fig. 4(a)). The first stress peak is due to the initially direct impact of the raindrop against the coating surface, while the second stress peak may be generated by the shock wave front after the high density liquid region is created [21]. Further study of the two-peak stress will be conducted.

![Figure 4. Coating von Mises stress corresponding to different (a) raindrop sizes, (b) impact speeds, (c) impact angles, and (d) raindrop shapes.](image)
Figure 4 (b) compares the von Mises stress under the normal impact (impact angle = 90º) of a spherical raindrop (diameter = 2 mm) with three different impact speeds (80 ms$^{-1}$, 100 ms$^{-1}$, and 120 ms$^{-1}$). The ratio among the three first-peak von Mises stress (30 MPa, 50 MPa, 74 MPa) is approximately equal to the ratio among the square of the impact speeds (80 ms$^{-1}$, 100 ms$^{-1}$, and 120 ms$^{-1}$), which is consistent with the relationship between the kinetic energy and the impact speed (i.e., kinetic energy = mass × speed$^2$/2). However, the second stress peak is not significantly influenced by the impact speed as shown in Fig. 4 (b).

Due to the wind turbine blade rotation and complex weather condition (e.g., wind effect), the raindrop could impact the wind turbine blade with varied angles. The normal and tangential loads exerted due to perpendicular impact and inclined impact, respectively, could naturally create different stress distribution in the blade coating. In order to investigate the influence of the impact angles on the stress, a spherical raindrop with diameter of 2 mm and impact speed of 100 ms$^{-1}$ is used to impact the blade panel with three different impact angles (30º, 60º, and 90º). Figure 4 (c) shows that, as the impact is inclined, the stress is dramatically reduced, especially for the first peak stress. It is worth noting that we only consider the raindrop impact on the smooth surface and has not considered the realistic surface roughness which will have important influence on the stress and erosion induced by raindrop impact. Nevertheless, the current results indicate that non-perpendicular raindrop impact could dramatically reduce the impact stress, consequently reducing the fatigue damage.

Due to surface tension, external and inertial forces (e.g., wind force and gravity force), raindrops normally have different shapes when impacting wind turbine blades. In this paper, the equilibrium shape of raindrops is described by the axis ratio $\alpha$, a ratio of the minor axis to the major axis of the ellipse [22]. In the measurements of Pruppacher and Beard, the axis ratio $\alpha$ is found to have a linearly decreasing relationship with the equivalent spherical radius $a_0$ in 1 to 9 mm diameter, expressed as [22]

$$\alpha = 1.030 - 0.124a_0$$

Figure 4 (d) compares the von Mises stress under three different raindrop shapes (sphere, ellipse-x indicates the ellipse’s co-vertex first impact the blade panel, ellipse-y indicates the ellipse’s vertex first impact the blade panel) with the same volume ($4/3 \times \pi \times 2^3$ mm$^3$) and the impact speed (100 ms$^{-1}$). As shown in Fig. 4(d), the non-spherical droplets result in increased first peak stress and reduced second peak stress, although the three raindrops have the same volume.

3.2. Impact stress calculation considering a rain event

In a real rain event, a significant number of raindrops with varied sizes, shapes, and speeds are randomly impacting on wind turbine blades. For a single raindrop impact simulation by SPH, it costs 2 hours using a computer (Intel(R) Core(TM) i7-8750H CPU @ 2.20 GHz Processor, Memory (RAM) 32 GB, 64-bit Windows Operating System). Thus it is not practical to conduct SPH simulation of a rain event with a large number of raindrops randomly impacting on wind turbine blades. When calculating impact stress due to a stochastic rain event, hereafter we assume that: 1) the shape of raindrops is spherical disregarding other types of shapes (e.g., ellipse, semi-oblate and parachute forms) and 2) the raindrops are vertically colliding with the wind turbine blade ignoring different impact angles. To tackle the computational issue, we develop an interpolation method to efficiently and accurately obtain impact stress of the panel under a rain event. The method utilizes pre-calculated impact stress due to simple raindrops impact. Detailed steps are explained as follows:

Step 1: Conduct a series of single raindrops impacting at the center of the top coating of the blade panel. Herein we conduct 20 single raindrop impact cases using raindrop sizes of 0.5 mm, 1 mm, 1.5 mm, 2 mm, ..., 10 mm.

Step 2: Create a stochastic rain field by following the method presented in Section 2 given a rain intensity and a rain duration.

Step 3: Calculate the impact stress of a random raindrop by interpolating the SPH impact stress of the single raindrops with close diameters from Step 1. After identifying the size and location of the random raindrop, a circular domain with the impact point as the center and 10 times
of the raindrop diameter as the radius is considered as the area influenced by the raindrop impact. The stress inside this circular domain are then interpolated based on stress results of the closest four cases in terms of the raindrop diameter from Step 1.

Step 4: Repeat Step 3 for calculating impact stress due to other raindrops.

As a demonstration, Fig. 5 shows an interpolated stress when a random raindrop with diameter of 2.8 mm impacting at the top-right corner of the panel. Figure 5(a) shows the time series of interpolated von Mises stress of the raindrop (diameter = 2.8 mm) and those of SPH von Mises stress of the closes four raindrops (diameter = 2, 2.5, 3, 3.5 mm). As illustrated in Fig. 5(b), it is observed that the interpolated stress component matches well with the stress directly calculated by the SPH approach. Figure 5(c) shows the contour of the interpolated stress component ($s_{11}$). Thus, the multi-axial non-proportional complex stress states under a stochastic rain field are accurately and efficiently calculated and are used for the following fatigue analysis.

4. Fatigue analysis

For the coating material, the von Mises stress is used to handle the multiaxial stress state in the fatigue damage calculation. In order to address the fatigue damage calculation under different stress ratio, the
von Mises stress obtained from the FEA is further converted to an equipment von Mises stress that can be used to predict fatigue damage based on S-N curves, which is obtained from zero-mean stress fatigue test (stress ratio equals to −1). The linear Goodman relation is used to calculated the equipment von Mises stress expressed as

\[ \sigma'_a = \frac{\sigma_a US}{US - \sigma_m} \]  

(6)

where \( \sigma'_a \) is the corrected equipment stress amplitude, \( \sigma_a \) is the original stress amplitude, \( \sigma_m \) is the mean stress and \( US \) is the ultimate tensile strength for positive mean stresses (for negative mean stresses \( US \) is the ultimate compressive strength). In this paper, the following S-N curve referred from [23] is used,

\[ \sigma_a = 42.48N^{-0.0344} \]  

(7)

The accumulated fatigue damage \( D_{coat} \) is then calculated based on the Miner’s rule

\[ D_{coat} = \sum_{i=1}^{j} \frac{n_i}{N_i} \]  

(8)

where \( j \) is the number of stress levels. The applied number of stress cycles, \( n_i \), is counted by the rainflow cycle counting method and the allowable number of stress cycles, \( N_i \), is calculated by the prescribed S-N curve. As shown in Fig. 6, the fatigue damage of the top coating of the blade panel is calculated under a rain event determined by a rain intensity of 1 mm/h and a rain duration of 0.5 hour. As the raindrops are uniformly distributed in the simulated stochastic rain field, the investigated blade panel has no concentrated fatigue damage-critical zones. The averaged fatigue damage of the coating is in the magnitude of \( 10^{-3} \).

**Figure 6.** Predicted fatigue damage contour of the coating under a rain event determined by a rain intensity of 1 mm/h and a rain duration of 0.5 hour.

5. Conclusions

This paper presents a computational model of wind turbine blade erosion induced by raindrop impact. Key concluding remarks are provided as follows:

(1) Rain events are simulated by a stochastic rain texture model that use rain intensity and rain duration as the inputs;
(2) Single raindrop impact is analyzed by a smoothed particle hydrodynamic approach. The obtained stress waves reveal the stress propagation in the top coating and through the thickness of the investigated wind turbine blade panel.

(3) The influence of the raindrop size, impact speed, impact angle, and raindrop shape on the impact stress are investigated by carrying out the SPH analyses of representative cases. A stress interpolation method is proposed to accurately and efficiently calculate the impact stress under a random rain event.

(4) The fatigue damage of the top coating material is evaluated under a rain event simulated according to the rain intensity and the rain duration.

The current research lays the groundwork for predicting the blade fatigue life due to rain erosion and proposing new maintenance strategy to prevent blade erosion. Future work may include:

1. Investigate the influence of raindrop impact on the damage of internal composite materials of wind turbine blades which involves fatigue analysis considering non-proportional multi-axial complex stress states;

2. Estimate the fatigue life of wind turbine blades due to rain erosion considering long term precipitation data.

3. Experimental work on blade erosion due to raindrop impact has to be carried out (or referred from literature) to validate and improve the computational blade erosion model.

4. Apply the computational model for designing new blade coating and optimal blade rotation control to reduce the rain erosion for large wind turbine blades.

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