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Department of Aerospace Engineering

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MEC449 ADVANCED ENGINEERING FLUID DYNAMICS

CASE STUDY AREA 2: AIRBORNE PARTICULATE FLOWS OVER WIND TURBINE BLADES

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1.FLUID MECHANICS OF THE PROBLEM

During their life, wind turbines are exposed to environmental conditions which can lead to erosion of the blades. One cause is rain droplets. As shown in figure 1.1 when the liquid droplet impacts the surface of the turbine blade three stress waves emerge; a compressional wave, a shear wave and a Rayleigh wave, which is confined to the surface [2]. The propagation of these waves is considered as one of the main mechanisms with which high-speed droplet impact can cause failure [3]. The other important phenomenon that occurs during the impact moment is water hammer pressure, which is a function of liquid density, the speed of sound and the impact speed of the droplet. Shortly after the moment of impact, lateral jetting occurs as a first step of depressurising the droplet and plays an important role in the initiation of the erosion damage as it can potentially tear surface irregularities [3].

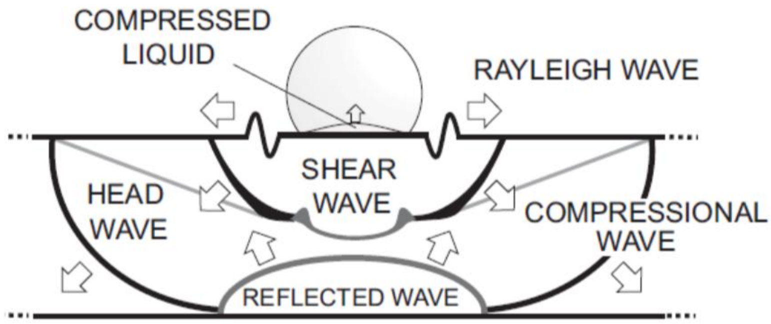

Figure 1.1 Schematic of three waves propagating following the impact of a droplet on a surface. Source: adapted from [4]

Airborne sand particulates can also have a damaging effect to the turbine blades. Upon impact, sand grains promote a mechanism of surface abrasion and is responsible for an increase in blade surface roughness and a decrease in structural stiffness [5]. Although the mechanisms that cause the damage to the blade by water and sand particles are different, the consequences to the performance of the turbine are similar. Aerodynamically a change in roughness and surface profile can lead to early boundary layer transition and early stall. Sareen at al. [6] investigated these consequences and found that leading edge erosion of a wind turbine blade can increase drag by 6-500% and substantially reduce lift resulting in a loss in energy production.

2.RELATED WORK

Due to the issues caused by leading-edge erosion and the ever-increasing demand for wind energy, there has been a significant amount of research and engineering effort to protect and prolong the life of wind turbine blades. In 1996, Weigel [7] identified and tested two new hydrolysis-free elastomeric materials which outperformed the current helicopter blade materials with regard to sand and rain erosion. Although, this was not tested on wind turbine blades, similar leading-edge erosion does occur on helicopter blades and therefore the results from this could be transferable.

In 2010, Karmouch et al. [8] covered wind turbine blade surfaces with a superhydrophobic coating and found it to be a suitable candidate for water protection, which one could assume would mitigate against rain erosion, however, was not looked at in the study. Simon at al. [9]

and Armada et al. [10] discuss the idea of adding various nanosized reinforcing particles to blade protective coatings with the intention of improving the erosion resistance. In 2012, Sareen et al [11] concluded that using leading-edge protection tape was far less detrimental to the performance of the airfoil performance than leading-edge erosion, however the backward facing step of the tape did cause some performance loss itself and was suggested that this could be minimized by extending the tap further back from the leading edge and possibly integrating it with the blade.

In 2015, Valaker et al [12] tested and compared 2 industrial and 3 proposed droplet erosion protection coatings. It was found that the industrial coatings did not perform as well as the proposed ones and one of the proposed coatings did not show any sign of failure. However, it was concluded more testing was critical. After reviewing coating life models Slot et al. [13] recommended developing blade surfaces with a low modulus of elasticity or coatings with adjustable compressive stresses and hardness or without defects and impurities. In 2017, Cortés et al. [14] found that flexible coatings were far superior to rigid gel coating for erosion protection. This was further backed up by Herring et al [15] when discussing the advantages and disadvantages of existing protection solutions. However, both gelcoats and flexible coatings, along with protection tape were outperformed by erosion shields in the 2019 review [15], where it was suggested a redesigned integrated metallic erosion shield may offer the solution to solving leading edge erosion.

Fiore et al. [5] investigated the optimization of wind turbine aerofoils subject to sand erosion and concluded that an optimum aerofoil geometry would mitigate the effects of the erosion as the blade ages and allow for the wind turbine to operate at higher values of $(C_l/C_d)_{max}$ in the turbine initial clean conditions. Bech at al. [16] presents the idea of reducing the tip speed of the blades during extreme precipitation conditions events to reduce the impact of particles, therefore increasing the service life of the leading edge and concluded the energy sacrificed during the reduced speed time is marginal in proportion to that lost due to eroded blades. Menezes, E.J.N. et al. [17] review three main control mechanisms used to increase efficiency and cost-effectiveness of wind turbines. Although this paper has no mention of leading-edge erosion, the concepts involved could be used to counteract some of the effects caused by it. For example, altering the pitch of the entire blade to reduce the angle of attack could avoid early stall.

In recent years there have been discussions about using digital twin technology to stretch the life of wind turbines, however it would not appear to be in the context of leading-edge erosion leaving a gap in knowledge to be explored. A digital twin is a virtual model of a process, product or service [18]. Articles from TWI Ltd [19] and Recharge [20] discuss the idea of using digital twin technology for real-time assessments of the structural conditions of wind turbines in order to extend their lives by employing the appropriate maintenance when needed.

3.PROPOSED RESEARCH AREA

As mentioned above the use of digital twins in the context of leading-edge erosion is yet to be explored. By creating a digital twin of a wind turbine or wind turbine farm it is possible to get a real-time visualisation of everything that is going on. Sensors could detect wind speed or precipitation levels and adopt the reduced tip speed technique Bech et al. [16] proposed or use one of the control mechanisms reviewed by Menezes, E.J.N et al. [17]. The real-time assessment mentioned in the articles from TWI Ltd [19] and Recharge [20] could potentially be used to detect leading-edge erosion meaning as soon as it occurs the appropriate maintenance i.e. protection tape could be employed, instead of having to wait for the routine checks which may not happen very regularly.

In order to explore this concept firstly a systemic search of literature relating to the subject should be carried out. To cover all aspects and relevant topics the following key words could be used to find the appropriate literature; “Digital Twins”, “Digital Twin Technology”, “Erosion Sensors”, “Digital Twins of Wind Turbine Blades”. It may also be useful to see if this concept has been adopted for similar subject areas such as gas turbine engines and looking into whether the same techniques could be applied. One piece of literature which could be included in the review is *Predicting Wind Turbine Blade Erosion using Machine Learning* [21] as concepts from here could be used.

The major limitation of this concept, after whether it is achievable of course, is the cost. Implementing digital twin technology requires lots of sensors and software etc meaning it requires substantial investment. Therefore, the cost of this must be compared to the cost of energy loss due to leading edge erosion.

Word Count: 1250

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