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Modelling and empirical development of an anti/de-icing approach for wind turbine blades through superposition of different types of vibration

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ABSTRACT

The generation of green, safe and inexpensive energy by wind turbines is often decreased or interrupted in severe climate areas during cold weather. When the blades are even partially covered by different types of ice, their efficiency drops suddenly due to degradation of the blade profile from the ideal. The present study presents a new approach using ultrasonic guided waves as an anti/de-icing technique supplemented by low-frequency vibrations to effect shedding of the ice from the turbine blades. The study consists of a series of steps including initial theoretical studies and finite element simulation of representative plates and turbine blades, followed by a number of experimental validations concluded by tests of the complete approach in an icing wind tunnel. The results show the efficacy of the developed approach in tackling the different types of ice which can form on the blades, using very low power compared to available thermal techniques.

1. Introduction

Today, wind energy is an efficient source of green power. The relatively cheap and reliable harvest of this energy has extended its use into wide geographical regions, even those with an icing climate. However, power generation by wind turbines in such regions usually suffers from the harshness of the weather in mid-winter when the wind turbine blades are subject to ice formation. It has been well reported that ice accretion on wind turbine blades can drop the turbine efficiency and reduce output power (Rindeskär, 2010; Laakso and Peltola, 2005; Sørensen and Sørensen, 2011). To solve the icing problem, a range of techniques has been developed and applied to date. Thermal technologies including electrical resistance heating and hot air circulation have shown some success but they are usually energy inefficient as they consume considerable amounts of energy themselves. For example, hot air circulation can use up to 15% of the turbine's nominal output power (Laakso and Peltola, 2005). Some attempted/proposed methods such as microwave heating have poor performance (Sørensen and Sørensen, 2011). Likewise, other available techniques including coating and painting blades, use of anti-freeze chemicals and active pitching are associated with major drawbacks such as excessive heat absorption, damage risk to structural integrity of the blades and environmental pollution (Kimura et al., 2004).

In this work, an approach has been proposed and tested to overcome the icing problem effectively for the blades of a 75 kW wind turbine using relatively little energy. The technique exploits the advantages of two previously attempted techniques in a synergistic way to cover up each other's deficiencies. These two techniques are ultrasonic guided waves (UGW) and low-frequency vibrations (LFV). The main action is carried out by application of UGW, which has been used for non-destructive testing for many decades but is relatively new as an ice protection technique. Guided waves are considered as the long-range waves propagating through materials in which vibrations of high frequency compared to LFV are created on the surfaces. The technique of UGW has recently been considered to be developed, improved or adapted in different ways for protecting surfaces against icing (Gao and Rose, 2009; Palacios, 2008; Overmeyer et al., 2013). The idea in this approach is to induce shear stress at the interface of the ice with the blade's outer surface that is sufficient to de-bond the accreted ice layer. The challenge is how to excite the appropriate waves that generate such an effective stress on the material surfaces. This depends on factors such as wave mode, excitation frequency, direction of excitation and the arrangement of a possible transducer array, and requires that the dispersion curves of the propagating waves be extracted and analysed. The analysis can be very complicated due to the complex geometry of the blade. Moreover, it is very important to select an optimum frequency and wave mode at which minimum power is consumed consistent with the required shear stress at the ice layer/blade substrate being produced. For this reason, a so-called interfacial stress concentration coefficient (ISCC) factor has been developed previously

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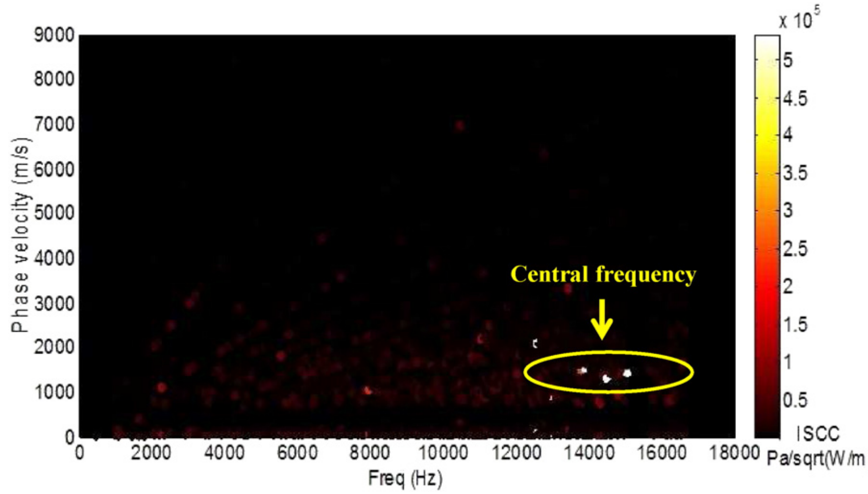

Fig. 1. Dispersion of a 7-mm-thick blade's leading edge with a 2-mm-thick layer of glaze ice superimposed with ISCC values.

to characterise the wave mode, minimal power and frequency maximising the shear stress induced at the interface (see Zhu, 2010 for details). The ISCC values should then be superimposed with dispersion curves to complete the criteria for selection of excitation frequency. According to the definition of ISCC, the higher the ISCC, the more shear stress can be induced at the ice interface. So, a frequency band with a high ISCC value is the first criterion. Dispersion is normally defined as the dependency of the wave velocity on the frequency at which the wave propagates in a medium. One of the desirable characteristics for an ideal wave mode in UGW applications is having lower dispersion, i.e. the less variation of wave properties with frequency. In addition, it is very important to avoid energy dispersion and dissipation by selecting a non-dispersive frequency range for the wave mode. Moreover, it should be noted that dispersive wave modes undergo more attenuation and therefore less coverage than non-dispersive ones. So the second criterion to be taken into account is selection of a wave mode without any or with minimum dispersion.

The complementary action in this approach is provided by LFV, which was first utilised by Bell Helicopter to tackle ice formation on helicopter blades (Coffman, 1987). It showed successful results on the blades except in the vicinity of the leading edges. In the current work, LFV plays a supplementary role to ensure that the ice will be shed simultaneously with or immediately after the ice/substrate bond is weakened by UGW action. The idea is based on the generation of high accelerations, from 25 g to 30 g, enough to cause stress at the blade surface. These levels of acceleration and stress can be reached at a frequency close to one of the first 4–6 natural frequencies of the blade between 0 and 50 Hz. It should also be stated that the wave frequency must not match the resonance frequency precisely due to possible risk of damage to structural integrity of the blade. Accordingly this level of vibration should not be applied for more than two seconds to prevent reduction in fatigue life according to the original studies in this area (Coffman, 1987).

In the following section, a summary of the computer simulation and numerical modelling will be presented. Then, some of the prominent results from laboratory trials that validate the model findings are illustrated. Finally, the experimental setup and outcome of this new approach in an icing climatic chamber will be demonstrated.

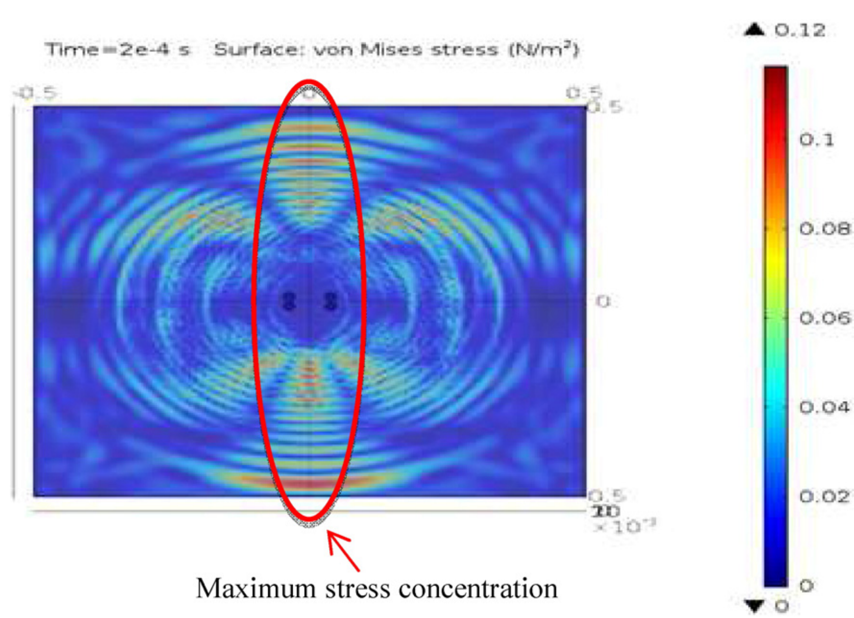

Fig. 2. Aluminium plate with 2-mm-thick glaze ice at 150 μs.