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A dual de-icing system for wind turbine blades combining high-power ultrasonic guided waves and low-frequency forced vibrations

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ABSTRACT

Wind turbines mounted on cold climate sites are subject to icing which could significantly influence the performance of the turbine blades for harvesting wind energy. In this study, an innovative dual de-icing system under development is described. This either prevents ice accumulation (anti-icing) or removes any ice layer present on the surface of the blade material (de-icing). A modelling study on ultrasonic guided waves propagating in composite blades was used to determine the optimal frequency and location of the transducers for ensuring wave propagation, causing the required level of energy concentration and resulting shear stress across the leading edge of the turbine's blade. In parallel, the effects of low frequency vibrations have been investigated through modal and harmonic analyses. This allowed specification and optimisation of the positioning of shaker(s), together with the magnitude and direction of harmonic forces required to induce sufficient acceleration to the blade surface for ice removal. An appropriate survey was also carried out to evaluate the potential for fatigue failure of the blade due to harmonic forces induced by shakers. The proposed technique configures and presents an active solution for the icing problem, allowing safe and reliable operation of wind turbines in adverse weather conditions.

1. Introduction

Nowadays wind energy is one of the leading renewable energy sources. An important issue is the location of sites which are sufficiently windy to gain maximum efficiency. However many areas offering high potential for harvesting wind energy are exposed to low temperature over winter and this, together with the resultant icing, affects the operational performance of wind turbines. One of the major problems is ice accretion on turbine blades which produces significant change in the aerodynamic geometry of the blade's surface. As a result, it can considerably reduce the efficiency of wind turbines. Furthermore, icing can cause imbalance in blades leading to increased wear in structural components such as connectors, couplers, gearbox etc. Safety hazards may also result, especially in residential areas, as large pieces of ice may be thrown from turbine blades during operation. In extreme cases, turbine operation may have to be halted until weather conditions become suitable, affecting overall energy production.

To alleviate the above-mentioned problems raised by ice formation on turbine blades a number of techniques have been developed and tested to anti-ice and/or de-ice the blades. Methods in current use include surface coating, antifreeze chemicals, electrical resistance heating, hot air circulation, pulse electrothermal de-icing, manual chip-off, etc. However there are drawbacks and limitations for the full industrial uptake of these methods. For example, chemicals do not remain on the blade surfaces for a long time period and even coated surfaces cannot effectively prevent ice formation [1]. Also all existing thermal de-icing methods demand a high level of power to operate. Consumed power may reach 12% and 15% of the turbine's nominal power output in the cases of electrical resistance heating and hot air circulation respectively [2]. Apart from the issue of energy consumption, the high temperature induced in the blade by thermal techniques may pose a serious risk for the integrity of composite blades [2]. Other developing methods such as microwave heating have either poor performance or low energy efficiency [3]. The drawbacks and limitations of existing ice control approaches indicate the potential for development of a new reliable and cost-effective de-icing technology.

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A relatively new strategy used for ice protection systems is ultrasonic guided waves (UGW) for which a few research projects have recently been reported [4–6]. This method is well known for non-destructive testing applications in which the waves propagate in a low frequency range (typically between 20 and 100 kHz for long-range ultrasonic testing). Based on wave theory, ultrasonic waves cause displacements and stresses inside a material as they propagate through it. Therefore they have the potential for removing ice accumulated on different surfaces. For example, Venna et al. [7] applied ultrasonic waves of 1 kHz frequency on an aluminium airfoil structure which matched its resonance frequency and de-iced the airfoil. They could manage to shed off the ice 130 s after excitation of piezoelectric excitation patches. The shear and normal stresses measured during their experiment for achieving this reached 7.5 MPa and 25 MPa respectively. JL Palacios [8] tested ultrasound waves for helicopter blade anti-icing and de-icing using two distinct modes: transverse and shear, which were effective on leading edges at both short range and over longer distances. For short distances near the transducers, de-icing results were excellent using ultrasound powers of up to 0.37 W/cm^2 which is very energy efficient compared with thermal ice protection systems. Part of the current research has been built on this previous research.

Another technique associated with the current work is low-frequency vibrations whose background dates back to 1978 when Bell Helicopter performed a feasibility study on the application of mechanical vibrations to prevent ice accretion on helicopter blades [9]. In that research, an electric motor was used to vibrate a helicopter's main blade in beamwise and/or torsional modes close to the blade's major natural frequencies to induce maximum excited energy into its structure. It was found that harmonic forces generating acceleration of 25–30 g at a low frequency range between 0 and 50 Hz could lead to satisfactory de-icing. Results for de-icing of the helicopter blade proved to be more effective in the most critical areas of the blade near to the hub while being less efficient at the leading edge. However, for wind turbines, the leading edge of the blade is of high importance for de-icing or protection against freezing [5,9]. Hence the dual system which has been studied here combines low frequency vibrations and ultrasonic waves in an attempt to provide total blade coverage. An efficient de-icing system that does not impair structural integrity while providing deicing for the entire structure of the blades is desirable. For this reason, in parallel with deicing potential, the potential reduction of the blade's life due to fatigue effects has to be considered.

2. Current vibratory deicing approaches

2.1. Overview

As mentioned above, earlier attempts to deice helicopter blades have shown that low-frequency vibrations are highly effective in de-icing across the blades except at the leading edges, whilst the application of ultrasound (US) have been proved to be very good at de-icing merely at surfaces such as the leading edge of the blade where the US power density is high. Hence the present work, as its main innovation, combines these two techniques, so that one subsystem will compensate for the deficiencies of the other. This approach provides sufficient energy induced to the blades through both internally exciting particles of the material and externally shaking the whole structure. In the former case, wave propagation towards the leading edge causes the shear stress required to break the ice-substrate bond while in the latter, acceleration generated in the blade causes the ice to be shaken off. The system is estimated to consume low power to fulfil these tasks, which is another advantage. This point will be briefly explained in the sample results.

The present work focused on modelling to develop a reliable ice protection system for anti-icing and/or de-icing wind turbine blades. Simulation plays a crucial role in designing the system as it should verify that the waves can propagate through a composite blade. Also the harmonic forces and the locations of the shakers need to be determined to check whether or not they can generate sufficient acceleration in the critical areas of the blade without causing serious damage. The fatigue life of the blade due to low-frequency vibrations caused by shakers is potentially significant and should be investigated. In fact, since the first mode shapes of the blade structure particularly with frequencies below 50 Hz are crucially important, previous studies on the fatigue analysis of wind turbine blades have been mainly based on these frequencies (see, for example, [10–12]). Fatigue analysis in the current work has been carried out for different scenarios in forced vibrations to confirm that the new approach does not endanger wind turbine blade structural integrity.

Fig. 1 outlines the steps taken in developing the ice protection system in the current work. The relevant details for each term along with modelling procedure are presented in the following sections.

2.2. Ultrasonic guided waves

Preliminary research on helicopter blade de-icing via ultrasonic guided waves was carried out by Palacios et al. [8,13]. The idea is the induction of shear stress in such a way that interfacial stress between ice and substrate exceeds the adhesion strength between them. However the question was how to generate such a stress that exceeds the bond strength while reducing the in-plane shear stress inside the substrate to avoid any damage to the blade. The resolution found for this challenge was presented through the concept of Interfacial Stress Concentration Coefficients (ISCC) to calculate the normalized interface shear stress for different combinations of ultrasonic guided wave modes and frequencies [4]. In fact, ISCC is a value used for assessing the capability to induce enough stress into the interface for a given amount of power. In other words, ISCC is a normalized value to optimize frequency, mode and power for generating maximum interface shear stress. For this reason, the current work considers this value as one of the main criteria in the following analyses and simulations regarding ultrasonic guided waves. Therefore dispersion curves with ISCC were first calculated to investigate the best frequency and wave mode, then an analysis of power concentration and stress distribution was conducted.

By modelling the complex vibration modes present in the different sample configurations, it was possible to determine a dispersion curve and predict the dispersive properties of each blade configuration or plate structure to a reasonable level of accuracy. This was performed using eigenfrequency and time dependent analysis in the structural mechanics module. An eigenfrequency analysis is an effective tool for describing natural behaviour for a structural geometry when resonating. In addition, time dependent analysis was used to investigate the transient power and stress distribution and ultrasound propagation generated from transducer arrays.

An eigenfrequency analysis based on FEM provided the mode shape and natural frequency information. Two critical parameters were still required in order to plot a dispersion curve: phase velocity and wavelength. Wavelength could be determined by observing the mode shape for each eigenfrequency. Wavelength defines the distance travelled by a complete wave (1 peak and 1 trough), and the phase velocity at that frequency could therefore be calculated using the following equation.