Applied Acoustics 114 (2016) 19–26

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Numerical simulation and experimental validation of ultrasonic de-icing system for wind turbine blade

Congbo Yin [a,*], Zhendong Zhang [a], Zhenjun Wang [a], Hui Guo [b]

[a] College of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[b] College of Automobile Engineering, Shanghai University of Engineering Science, Shanghai 201620, China

ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form 5 July 2016
Accepted 7 July 2016

Keywords:
Ultrasonic de-icing
Wind turbine blade de-icing
Reliability
Harmonic analysis
Ultrasonic transducers
Piezoelectric actuators

ABSTRACT

It is widely accepted that wind energy is clean and renewable. However, icing on the blade surfaces of wind turbines is a serious problem in cold regions, which greatly affects its performance. Therefore, it is important to prevent ice accumulation on the surface of wind turbine blade and remove it whenever necessary. In this paper, a new non-thermal method–ultrasonic de-icing for wind turbine blade is proposed. Firstly, baced on the theory of ultrasonic de-icing, the harmonic analysis of the structure of the composite plate-ice layered system is investigated using the finite element method. The simulation results showed that ultrasonic de-icing method is feasible for wind turbine blade de-icing purposes. Secondly, the de-icing experiment of wind turbine blades using piezoelectric actuators is carried out in the freezer at a temperature of −15 °C, results showed that the ice layer can be debonded from the surface of wind turbine blade by the commonly used piezoelectric transducers made by PZT-5. The optimal frequency of ultrasonic de-icing of wind turbine blade is also given; finally, the installation way of ultrasonic transducers on the inner surface of wind turbine blade is given.

1. Introduction

One of the main challenges associated with cold-climate wind energy is icing on wind turbines and a series of icing-induced problems such as production loss, blade pneumatic [1], and further mechanical vibration. The icing-induced problems are the potential causes of fatigue and safety issues. Some effective methods are designed to measure the growth of ice and to examine the ice formation situation with different kinds of ice sensor [2,3]. However, it is necessary to carry out further research to prevent ice accumulation and remove it whenever necessary. Many de-icing systems for wind turbine blade have been developed in last two decades [4]. With the advancement of science and technology, these systems can be broadly divided into two categories: passive methods and active methods. Passive methods take advantage of the physical properties of the blade surface to eliminate ice or prevent the formation of ice, while active methods use external systems and require energy power supply that is either thermal, chemical or ultrasonic method introduced in this paper. In summary, passive anti-icing system consists of two types: flexible blades and active pitching. (a) *Flexible blades*. Flexible blades are flexible enough to crack the ice loose. Blade flexing is known to help shed the ice [5]. However, there is little published information on this subject [5]. (b) *Active pitching*. Semi-active methods use start/stop cycles to orient iced blades into the sun [6]. The advantage of this system is that it may work in slight icing environments [6]. However, it has not been scientifically verified and may damage the wind turbines [6].

In summary, active anti-icing system consists of four types: heating resistance, warm air and radiator, flexible pneumatic boots and electro impulsive/expulsive [1]. (a) *Heating resistance*. It consists of electrical heating element embedded inside the membrane or laminated on the surface [6]. The idea is to create a water film between the ice and the surface. Once created, centrifugal forces will throw the ice away [7]. This system has been used successfully in the aerospace industry for many years. Thermal efficiency is close to 100% because of direct heating [8]. Energy demand does not increase with blade size [7]. However, this system is still at the prototype level because of the limited market [9,10]. (b) *Warm air and radiator*. It blow warm air into the rotor blade at standstill with special tubes [11]. The idea is to develop a water film between the ice and the surface [1]. Once developed, it allows centrifugal forces to get rid of the ice [7]. The advantage of this system is that it works well in milder climates where icing occurs mainly at temperatures close to 0 [10]. However, this method consumes a lot of power at high wind speed and low

* Corresponding author.
E-mail address: yincongbo@usst.edu.cn (C. Yin).

http://dx.doi.org/10.1016/j.apacoust.2016.07.004
0003-682X/© 2016 Published by Elsevier Ltd.

temperature. (c) *Flexible pneumatic boots*. Flexible pneumatic boots in ate to break ice. In the normal non-inflated state, tubes lay flat and conform to the airfoil surface on which the de-icer is bonded [1]. After the buildup of generally 6–13 mm of ice on the surface of the airfoil, flexible pneumatic boots are inflated with compressed air to break ice [1]. This system is installed on many aircrafts and has low energy consumption. However, it may disturb the aerodynamics by increasing drag and will cause more noise [1]. (d) *Electro impulsive/expulsive*. It consists of very rapid electromagnetically induced vibration pulses in cycles that flex a metal abrasion shield and crack the ice [5]. A spiral coil is placed near the surface of the prole. When current is applied to the coil, a magnetic eld is created between the coil and the thickness of the profile [1]. The result is a rapid movement of the surface and the expulsion of the accumulated ice [12,13]. This system is efficient and environmentally friendly with lower energy consumption. It also causes no interference with Hertz transmission and is easily automated [12,13]. However, it is a new technology that has not yet been tested on wind turbine blades. Ice expulsion is a potential problem [12,13].

Ultrasonic anti-icing/de-icing technique was first proposed by prof. Jose L. Palacios in 2004 [15]. In his research the use of ultrasonic shear and lamb waves for composite rotor de-icing were investigated. Such technique is based on the fact that the adhesive bond of ice-substrate interface is relatively weak in shear strength compared with the interface forces within composite blades. When high-energy ultrasonic waves travel through a plate-ice layered system, the shear stresses at contact surface or interface between the plate and ice layer, is caused by the difference of wave propagation speed produced due to difference of physical properties existed in ice and the plate. Such shear stresses can not only debond the ice layer but also break the ice layer. The piezoelectric actuators can be used to produce local shears at the locations of ice accretion to weaken the interface and subsequently de-ice the surface with normal impulse forces.

It can be found that most of the studies have been focusing on passive de-icing methods and active methods with heating and electro system, where the Ultrasonic anti-icing/de-icing mechanism has not been fully substantiated. So far, no mature ultrasonic anti-icing and de-icing equipment development has been reported yet. This technique is still in laboratory research stage. In this study, a new non-thermal method–ultrasonic de-icing for wind turbine blade is proposed and carried out in the freezer at icing conditions. Firstly, baced on the ultrasonic theory, the ultrasonic de-icing process is simulated using the finite element method, and the interrelation between frequency and different plane stresses for the composite plate-ice layered system is investigated. Secondly, the de-icing experiment using piezoelectric actuators is carried out to provide theoretic and experimental support for the earlier reality of wind turbine blade de-icing based on ultrasonic technology. The optimal frequency of ultrasonic de-icing for wind turbine blade and installation way of ultrasonic transducers on the inner surface of wind turbine blade is also given.

2. Theory and calculation

2.1. The principle of ultrasonic de-icing

Under the action of ultrasonic actuators, there are two kinds of waves propagate in the composite plate-ice layered system—lamb wave and SH wave, which can cause interface shear stress between ice and substrate. The composite plates-ice layered system is shown in Fig. 1.

The wave functions of lamb wave and SH wave can be written as:

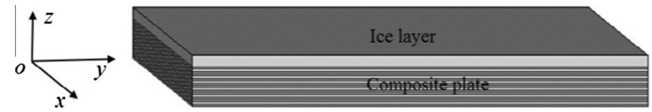

Fig. 1. The schematic of the anisotropic multi-layer structure.

$$\frac{\partial^2 u_i}{\partial t^2} = c_{ijkl}\frac{\partial^2 u_i}{\partial x_j \partial x_k} \tag{1}$$

In Eq. (1), ρ, c, u_i are the density, stiffness matrix and displacement field of the media respectively. Here, the elastic constant matrix (stiffness matrix) used in the calculation is listed in Eq. (2):

$$c = \begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} \tag{2}$$

Assume the displacement can be written as:

$$u_i = A_i e^{ik(x_1+px_3-ct)} \tag{3}$$

By solving Eq. (3) can obtain the solutions of SH wave and Lamb wave propagating in anisotropic elastic media. In Eq. (3), U_i is the polarization vector representing the displacement vector in each direction, k is the wave number along x_1 direction, c is the phase velocity along x1direction, and p is the ratio of the wave number in the x_3 direction with respect to the wave number in the x_1 direction. The guided waves are assumed to be propagating along the x_1-x_3 plane and the displacement is independent of the x_2 direction. Substitute the formal solution into the governing equation to obtain the Christoffel's equation, which is shown in Eq. (4).

$$\begin{bmatrix} \lambda_{11}-\rho c^2 & \lambda_{12} & \lambda_{13} \\ \lambda_{12} & \lambda_{22}-\rho c^2 & \lambda_{23} \\ \lambda_{13} & \lambda_{23} & \lambda_{33}-\rho c^2 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = 0 \tag{4}$$

Here, the values of λ_{im} (i, m = 1, 2, 3) can be obtained from Eq. (5):

$$\lambda_{im} = C_{iklm} n_k n_l \tag{5}$$

where n_k, n_l are the direction cosines of the normal to the wave front. Our purpose is to get a nontrivial solution for Eq. (4). The final solutions of the ultrasonic guided waves in the layered structure are the linear combinations of the partial wave solutions. Assume that the displacement and stress are expressed in Eq. (6) with undetermined coefficients A_k.

$$u_1 = \sum_{k=1}^{4} A_k e^{ik(x_1+p_k x_3-ct)} \tag{6}$$

$$u_2 = \sum_{k=1}^{2} A_k e^{ik(x_1+p_k x_3-ct)} \tag{7}$$

$$u_3 = \sum_{k=1}^{4} A_k U_{3k} e^{ik(x_1+p_k x_3-ct)} \tag{8}$$

$$\tau_{13} = \sum_{k=1}^{4} A_k [p_k + U_{3k}](ik) e^{ik(x_1+p_k x_3-ct)} \tag{9}$$

$$\tau_{23} = \sum_{k=1}^{2} A_k p_k \mu (ik) e^{ik(x_1+p_k x_3-ct)} \tag{10}$$

$$\tau_{33} = \sum_{k=1}^{4} A_k [\lambda + (\lambda + 2\mu) p_k U_{3k}](ik) e^{ik(x_1+p_k x_3-ct)} \tag{11}$$