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Progress on ultrasonic guided waves de-icing techniques in improving aviation energy efficiency

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ABSTRACT

Aircraft icing, in particular in-flight icing, poses serious threat to flight safety. Similarly, icing on blades of wind turbines is harmful to wind power systems as well. Therefore, the development of de-icing techniques has attracted significant attention in both Aeronautics and Wind Energy fields. Ultrasonic guided wave (UGW) de-icing technology, one of the mechanical de-icing technologies, features its light weight, low cost, drastic reduction in energy consumption, as well as its easy replacement and maintenance. Recent developments related to UGW de-icing technologies were summarized in this review, including latest studies on ultrasonic wave de-icing theory, advances in piezoelectric materials and transducers, and novel devices designed for de-icing systems. Some instructive experimental researches on ultrasonic de-icing method were introduced as well. Moreover, in particular, study on energy efficiency of ultrasonic de-icing method was introduced. Finally, some noteworthy problems, such as miniaturized transducers design, new type of the de-icing system design, and UGW de-icing mechanisms and its energy efficiency, were proposed for future investigation.

1. Introduction

Aircraft icing has been considered as a dangerous phenomenon posing significant risk to the safety of the flight. Water droplets accumulate on the airframe as ice under some specific meteorological conditions (clouds temperature: 0 to −20 °C, high liquid water content, and large diameter droplets) [1]. A typical cause of aircraft icing is the encounter of airplane surface with supercooled water droplets present in the atmosphere. These droplets impact the surface of aircraft structures and immediately freeze on the skin. Icing is inclined to occur at some significant parts of aircraft, such as leading edges of wing, tails, engine inlet, windshield, and helicopter blade [2,3] (shown in Fig. 1). Many researchers have indicated that ice accreted on these spots, in particular, on lifting surface, leads to aerodynamic configuration degradation [4,5]. Icing reduces aircraft efficiency by increasing weight, reducing lift, decreasing thrust, and increasing drag. With the accumulation of ice, the wing surface roughness increases, which not only results in airfoil distortion, but also induces boundary layer transition. Both friction drag and pressure drag increase substantially due to icing. For example, during a NASA flight research on Twin Otter (a twin engine type commuter STOL aircraft), a 43% increase in wing section drag coefficient was observed under a specific test condition. When in-flight icing leads to an increase in drag, aircraft engine requires providing extra thrust to overcome resistance, which necessitates additional fuel consumption. Specific fuel consumption is an important economic index which serious concern in aircraft design; therefore, increase in fuel consumption becomes a crucial problem that cannot be neglected. Besides, wing icing promotes boundary layer separation, thus decreasing lift and critical angle of attack. Still worse, icing on the horizontal tail seriously damages the stability and manipulation of airplanes [6]. Severe ice accretions may lead to disastrous fatal accidents [7,8]. To reduce the potential harmful effects of aircraft icing, a number of anti/de-icing systems have been developed. Thus, de-icing techniques are researched extensively in Aeronautical Engineering.

Similarly, this problem also exists in Wind Energy Engineering field. Wind energy is a significant renewable and sustainable type of resource [9]. However, accumulation of ice on wind turbines that work under harsh weather conditions, leads to deformation of blades which may cause increase of torque as well as crease of efficiency and power output [10]. Serious icing not only results in power outage, but also influences the stability and safety of power grid system. In view that the de-icing principles and methods of wind blades are similar to aircraft de-icing, some latest developments of de-icing technology in Wind

Abbreviations: UGW, Ultrasonic Guided Wave; NASA, National Aeronautics and Space Administration; STOL, Short Take-off and Landing; SHW, Shear Horizontal Wave; ISCC, Interface Stress Concentration Coefficient; FEM, Finite Element Method; PZT, Lead Zirconate Titanate; UHF, Ultrahigh Frequency; PVDF, Polyvinylidene Fluoride; TWG, Tailored Waveguides

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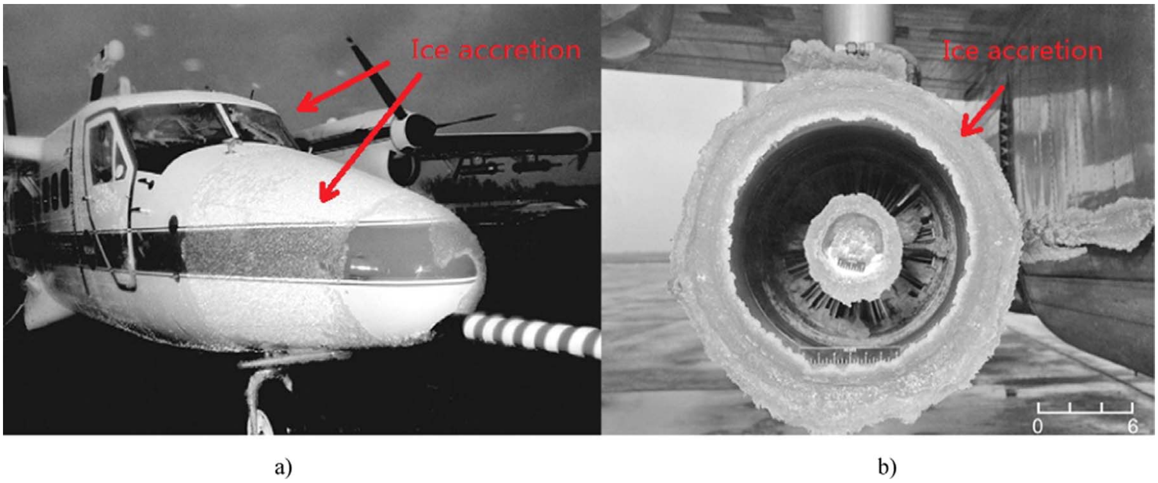

Fig. 1. Ice accretion on (a) windshield and nose (b) engine inlet (revised from [2], original courtesy of NASA).

Energy Engineering are also reviewed in the following parts of this study.

So far, several de-icing/anti-icing methods have been proposed, mainly including fluid anti-icing method, thermal de-icing/anti-icing method (electro-thermal and hot bleed air), mechanical de-icing method (electro-vibratory, microwave, shape memory alloy, pneumatic boots, and electro-impulsive), hydrophobic coating anti-icing method, and other de-icing/anti-icing methods [11,12]. Each of these methods has unique advantages and disadvantages (listed in Table 1) [11,13]. Among the seven items listed in Table 1, weight and power required are of particular concern in Aviation and Wind Energy Engineering. As summarized in Table 1, compared to other methods, ultrasonic guided wave (UGW) de-icing method consumes less energy and produces less weight increase. Therefore, comparatively, this technology exhibits significant development prospects in improving energy efficiency.

Ultrasonic techniques have been extensively studied and applied for aircraft icing researches. Ultrasonic wave could motivate high frequency vibration on skin of aircraft so as to remove ice. This method involves several components, including ultrasonic wave de-icing theory, piezoelectric materials and transducers, de-icing system design, and energy efficiency. These factors are, respectively, elaborated in the subsequent sections.

2. The ultrasonic guided waves de-icing theory

With the objective of guiding the ultrasonic de-icing system design, it is necessary to conduct theoretical investigation on ultrasonic de-icing principle. The research methods of UGW de-icing principle mainly include theoretical analysis, numerical simulation, and experimental test. Modeling accuracy is critically dependent on the accuracy of the input parameters [14]. Further, in this review these three aspects are systematically summarized, respectively, even though they are usually integrated and then applied in a research study.

2.1. Theoretical analysis

Currently, the effect of ultrasonic wave de-icing method is supposed to root in the following three main mechanisms: (1) mechanical stress, (2) heating effect, and (3) cavitation effect [11,15]. First, when ultrasonic wave excited by the transducers propagates in the thin plate structures with ice layer, shear horizontal wave (SHW) and Lamb wave are produced, which result in interfacial transverse shear stresses between the substrate and ice layer. If the shear stresses are greater than the ice adhesion strength, the interface between the structure surface and ice layer debonds. Second, thermal energy generated by UGW, because of internal damping losses of the substrate and ice, may result in the melting of some local areas of ice patch. Third, after microcrystalline melting, a thin layer of water is formed at the interface, wherein the formation and rupture of ultrasonic cavitation bubbles intensify the ice separation effect [15,16].

Among these mechanisms, the first one mentioned above is the most direct cause of ice removal. Moreover, the critical step of mechanical stress analysis involves the calculation of the shear stress of interface. To achieve this objective, the theories of elastic wave are usually employed. The governing equation for waves in solid media is given by Eq. (1) as follows [17,18]:

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

where ρ is the material's density, C_{ijkl} is the stiffness matrix, and u_i is the displacement field. The SHW mode propagation is shown in Fig. 2, where propagation of the wave is along x_1 and particle displacements are along x_2.

The general solution of Eq. (1) is assumed to be as follows:

$$u_i = U_i e^{ik(x_1 + \alpha x_3 - ct)} \tag{2}$$

where U_i is the polarization vector that represents the displacement vector in each direction, k is the wave number along x_1 direction, c is

Table 1
Comparison of anti-icing & de-icing systems for a Bell-412 model helicopter [11,13].

	Electro-Thermal	Fluid	Pneumatic	Electro-Impulsive	Electro-Vibratory	Microwave	Ultrasonic
Weight (lbs)	162	194	54	120	120	/	90
Ice accretion	Yes	No	Yes	Yes	Yes	No	Yes
Power Required(kW)	26	Negligible	Negligible	3.0	1.3	15	4.0
Performance Effects	10% torque rise	None	10% torque rise	10% torque rise	10% torque rise	/	None
Runback Potential	Yes	No	No	No	No	No	No
Detached Ice Impacts	Yes	No	Yes	Yes	Yes	No	Yes
Interference with Avionics	No	No	No	No	No	Yes	No