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Changes in the state of ice buildup on a composite plate: ultrasonic monitoring and assessment

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Abstract

From airplane wings to overhead power lines, through large blades of wind turbines, a buildup of ice can cause problems ranging from low performance to catastrophic failure. Therefore, it is of the utmost importance to control or prevent ice formation, especially on the critical areas of the structures. However, de-icing and anti-icing countermeasures can result energetically expensive and harmful to the environment. In addition, excessive use thereof will reduce the life of an ice protection system (IPS) and introduce fatigue to the controlled structures. Therefore, in order to manage properly the available resources, it is desirable to have an IPS that can both detect ice formation and monitor the ice thickness on critical surfaces. This would allow the IPS to operate when it is necessary. Ultrasonic guided-wave-based techniques have proved to be reliable for ice detection but approaches to assess ice state over time have not been reported yet. The present work investigates the interaction of ultrasonic waves, propagating in a composite plate, with an ice mass changing state, as it melts. The use of a metric is discussed as indicator of ice condition variation.

Keywords – Ultrasound, guided waves, ice melting, composite, piezoceramic transducer.

Introduction

Ice poses an operational, safeguarding, and safety threat to many structures and mechanical components. Indeed, an accumulation of ice on a wind turbine reduces the power produced, due to the greater surface roughness, which alters the air flow around the blades. In addition, an accretion of ice can cause a complete shutdown of the wind turbine, which may not be operational for a relatively long time. Finally, an imbalance in the ice load can lead to increased component wear and consequently increased maintenance costs. In the aviation field, the accretion of ice on the surfaces of an aircraft during the cold season leads to a decrease both in the maximum coefficient of lift and the slope of the lift curve and, at the same time, an increase in drag and critical stall speed. The tailplane may stall and experience a further decrease in efficiency, when the ice loading is asymmetrical. An accumulation can hinder the functioning of many other components such as radio antennas and pitot-static systems. In any case, it has been noted that even a thin layer of ice on a critical surface can be fatal. In the last decades, ice accretion has been a topic addressed by various studies whose salient points are reported. Hongerholt [1] demonstrated the ice sensing capability by ultrasound on wings in flight. Berbyuk [2] showed that ice formation has a significant influence on acoustic wave propagation. Gao and Rose [3] performed parametric studies highlighting how the initial formation of ice on the aluminum plate can be detected through the change in amplitude and time-of-flight in the wave signals. Rose [4] proved that the deposition of a thin layer of ice on top of the aluminum plate changes the phase velocity, concluding that guided waves can be used to detect ice accretion. Liu [5] examined the feasibility to characterize ice types (i.e., glaze or rime) on airframe surfaces by applying an ultrasonic pulse-echo method to measure a frequency-dependent

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attenuation coefficient. Mendig [6] also presented a method for the detection of ice in flight using ultrasound-guided waves. Memmolo and Moll [7,8] studied the interaction of guided ultrasound waves with ice layers. Their experiments demonstrated how ice perturbs the wave propagation in a solid medium, according to the excitation frequency, and highlighted the phase shift of the antisymmetric waves when the ice growths. Maio et al. [9] investigated the interaction of ultrasonic direct waves in composite plate with ice layers and the effects of ice thickening on the ultrasound propagation. Experiments highlighted that ice detection is strongly dependent on the excitation frequency. Moreover, according to this latter parameter, either early emerging or consolidated ice are better identified exploiting a detection index approach. Another technique based on electromechanical impedance and principal components analysis, proposed by Maio et al. [10], has also resulted to be effective to evaluate qualitatively the accretion of ice on a composite laminated structure.

The current paper aims to investigate the interaction between guided ultrasonic waves and a layer of ice that melts on a composite panel, through the experimental analysis. In particular, the defrosting process of the ice is monitored by the propagation of ultrasound at different frequencies. The data sets obtained from the experiments are post-processed in MATLAB environment with the use of an appropriate index suited to highlight the interactions between guided waves and the contaminant evolution and assess the ice state.

Experimental set-up and measurement procedure

In the study herein discussed, a rectangular composite plate is employed as test structure to carry out icing experiments. The plate is made up of six superimposed layers of non-crimp fabric (TRIAX KE 1175 g/m^2) produced by SAERTEX, each one having orientation 90°/±45, that realize a composite structure with orthotropic architecture. The resin is EPIKOTE MGS RIMR035c. The overall dimensions of the plate are length 62 cm, width 39 cm and thickness 5.2 cm, and an overall weight of 2269 g. Pairs of piezoelectric lead zirconate titanate (PZT) transducers are adopted to generate and sense ultrasound. Such PZTs, supplied by PI Ceramics, have a disc-shape and are bonded to the plate surface by using an epoxy adhesive (N64605, Pacer Technology's Pro). Their main characteristics are: diameter 10 mm, thickness 0.25 mm and material PIC255. Such a material is characterized by a high coupling factor, low mechanical quality factor and low temperature coefficient, which make it particularly suitable to generate and sense low power ultrasound. The composite panel is placed inside the CTS C-40/200 climatic chamber. A Handyscope HS5 (TiePie Engineering), including an arbitrary waveform generator, and a custom multiplexer, having 12 input/output channels, are exploited as data acquisition system. Such a system stimulates the selected PZT actuator by a five-cycle tone burst signal, once powered though a PD200 (PiezoDrive) spread spectrum amplifier. On the chamber ceiling, two cameras are installed to monitor the ice optically. A nebulizer is placed at 5 cm above the plate approximately, in order to create thin liquid films. By repeatedly spraying water and waiting for its freezing, an ice mass with thickness 4.8 mm is created on the panel. Such a mass constitutes a discontinuity, which modifies the material and geometric characteristics of the waveguide. Afterwards, the climatic chamber is switched off to promote the ice melting and guided waves are recorded over time. Figure 1 shows the relative positions of the transducers with a schematic representation both of frozen mass to be monitored and the involved transducer pairs. The ice monitoring by ultrasound is achieved by couples of PZTs, where one transducer generates guided waves, which propagate through the structure on which the ice is melting, while a different transducer is employed to sense the propagating waves (pitch-catch approach). In particular, the attention is paid to the feedback provided by three distinct pairs of transducers: the first pair refers to the transducers 1-2 (couple 1 or C1), the second pair regards the transducers 1-6 (couple 2 or C2) and the last one refers to 2-6 (couple 3 or C3). The actuator is in the first specified position, the receiver in the second one. Figure 1 highlights both propagation directions and the couples involved. It is worth noting that the couple C1, with respect to the others, allows evaluating the reflected energy from the ice. Otherwise, the remaining couples C2 and C3 allow assessing the transmitted energy through different ice amounts (e.g., when C2 is enabled, ultrasound travels through larger mass of ice). The measurements are performed continuously, from C1 to C3, and then start over. This procedure allows collecting three hundred measures for each couple, with a rate of one measure every seventy-three seconds (for a fixed couple). By analyzing these data, important information regarding the state of the ice can be extracted. In pitch-catch mode, the ultrasonic waves are detected by the receiver and measured as voltage-time signals. Therefore, such signals contain information on the traveled path, constituting a tool for ice localization too. Multiple excitation frequencies, ranging from 50 kHz to 300 kHz, are scanned by a step of 50 kHz, and all of them stimulate the symmetrical and anti-symmetrical modes generation.

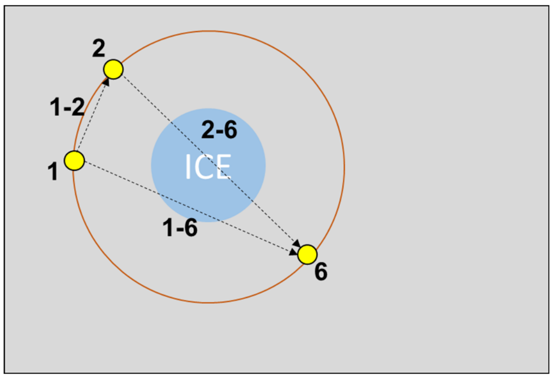

Figure 1 – On the left, panel front face schematization with transducers (the numbering is due to other PZTs available on the plate) and ice position. On the right, ice mass which melts when the climatic chamber is turned off (defrosting).

Metric for ice melting assessment

Based on the described measurement procedure, the data analysis involves three different pairs of transducers that interfere differently with the amount of ice placed on the panel. For the purpose, a metric is introduced to evaluate the variations between the baseline signal, collected when the ice is healthy, and each monitoring signal, gathered when the ice melts on the structure. The proposed parameter, herein called also *state index* (SI), is the energy of the difference signal, SI_{Energy}, which quantifies, in terms of energy, the difference between the baseline and the current waveform, as reported in equation (1):

$$SI_{Energy} = \sum_{i=1}^{N_{sp}} (x_{1,i} - x_{2,i})^2 \tag{1}$$

where $x_1(t)$ and $x_2(t)$ are the signals to be compared and N_{sp} is the total number of samples. Smaller the differences between the actual signal and the reference signal, the closer SI to zero and vice versa. This SI is used to post-process the data and preliminary investigate the interaction of ultrasound and melting ice to assess the current state.

Results and discussion

The current section shows the main results achieved implementing state index approach over defrosting period along with a discussion of the reasons for the trend of such a metric versus time. Figure 2 shows the SI based on the energy of the difference signal for transducer couples C1 (a), C2 (b) and C3 (c). The first one is mainly affected by the reflected energy from the ice, while the second and the last ones are mostly induced by changes in transmitted energy through the ice.

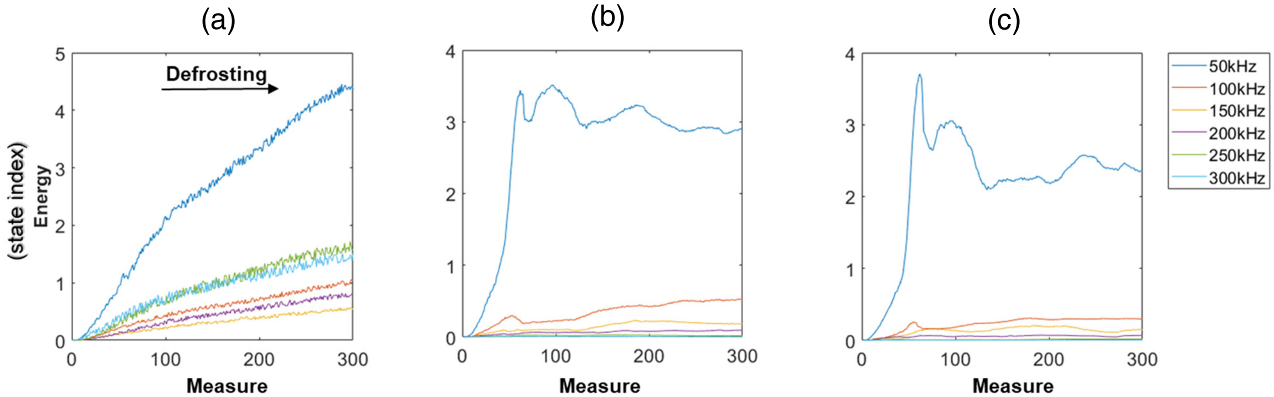

Figure 2 – Energy of the difference signal for couples C1 (a), C2 (b) and C3 (c).

As for C1, three different behaviors or regions can be highlighted. At the beginning, when the ice is still solid, there is no effect on wave propagation and SI is very close to zero. After a short time corresponding to a few measures, defrosting already affects the state index whose curve versus time shows a very high slope. Later, the curve shows a sudden change with a slightly lower slope, which means that ice condition variation affects the energy of the difference signal less.

It is worth noting that the frequency of excitation is an important influence parameter. Indeed, the highest sensitivity to defrosting is achieved when the lowest frequency is excited. That is mostly related to the A_0 mode, which shows the highest tuning [11,12]. Among other frequencies, the highest ones (250 and 300 kHz) still show a good sensitivity confirming a negligible effect at the very early stage of defrosting, the following high rate of change in SI and the final slope variation. It is worth noting that the two highest frequencies are characterized by the appearance of higher order modes [9]. This suggests that higher amplitude and higher mode occurrence benefit the defrosting detection. Instead, intermediate frequencies show the worst sensitivity to defrosting.

Taking a better look at the other two curves, it is possible to recognize a different behavior over time, with four different phases mainly. First, the defrosting effect is still negligible. Afterwards, the SI starts varying and then steeply rises showing an increasing slope. After a maximum being achieved, the energy of the difference signal oscillates with a general decrease. It is worth noting that the time when the defrosting starts affecting all the transducer couples is the same. In addition, the first maximum of SI and the following local minimum appear at the same instant both for C2 and C3, showing a similar behavior of the wave propagating across the ice layer. It is worth pointing out that for C2 and C3 the sensitivity to defrosting decreases with frequency progressively, showing major feedback at 50 kHz.

To further look into the physics behind these phenomena, in Figure 3 it is depicted the wave travelling from actuator 1 to sensor 2 (C1) in three different time instants representing different defrosting stages. The first one is recorded right after registering the baseline, namely when no change due to ice can be actually envisioned. The other ones are caught when defrosting keeps going. Through these different time instants, some characteristics of the signal change such as the amplitude and the phase.

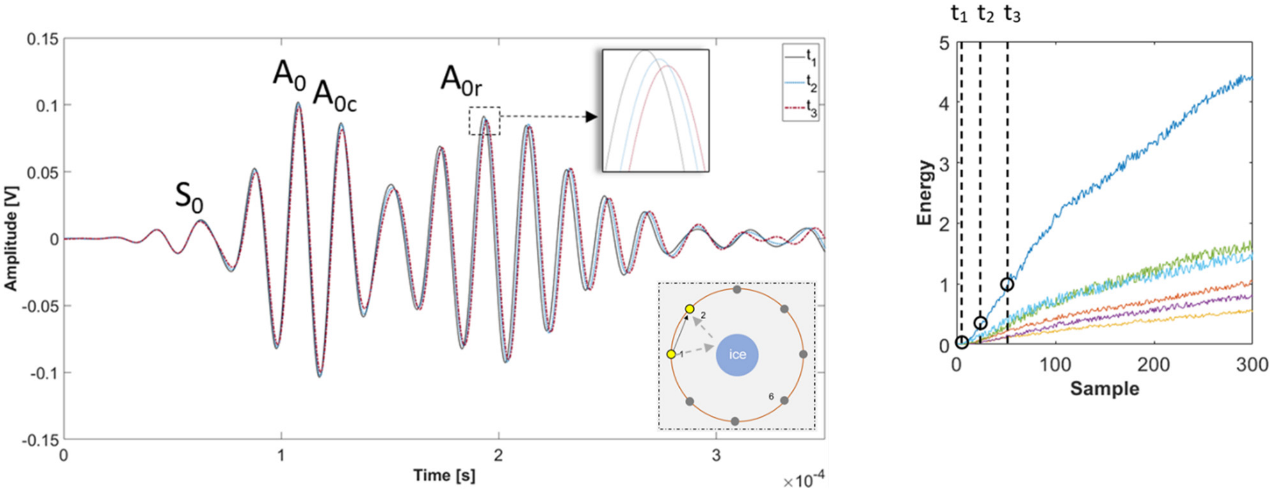

Figure 3 – Actual signals sensed by PZT 2 of C1, at different time instants ($t_1<t_2<t_3$), with magnification.

However, for a better understanding, it is worth discussing briefly on how ultrasonic guided waves interact with ice. Based on the time of flight (TOF) assessment, it results that: as a consequence of the incident fundamental mode A_0, an antisymmetric wave, A_{0r}, is reflected from ice. Secondly, a quite weak flexural wave A_{0c} travels back after that the S_0 generated by PZT 1 is converted and reflected at ice. Since S_0 is quite faster than the A_0 while travelling from PZT 1 up to the ice, A_{0c} is recorded first. However, the A_{0c} is not easily discernible because it is partially superimposed on both A_0 and A_{0r}. Although the S_0 is quite faster than A_0, the involved short distances return a similar round trip time of the waves. It is worth noting that the amplitude of A_{0r} is quite smaller than one of the incident wave A_0. This is due to part of the energy that is transmitted through the ice. Moreover, in this scenario, during defrosting both A_{0c} and A_{0r} show changes in amplitude and phase, as highlighted in Figure 3.

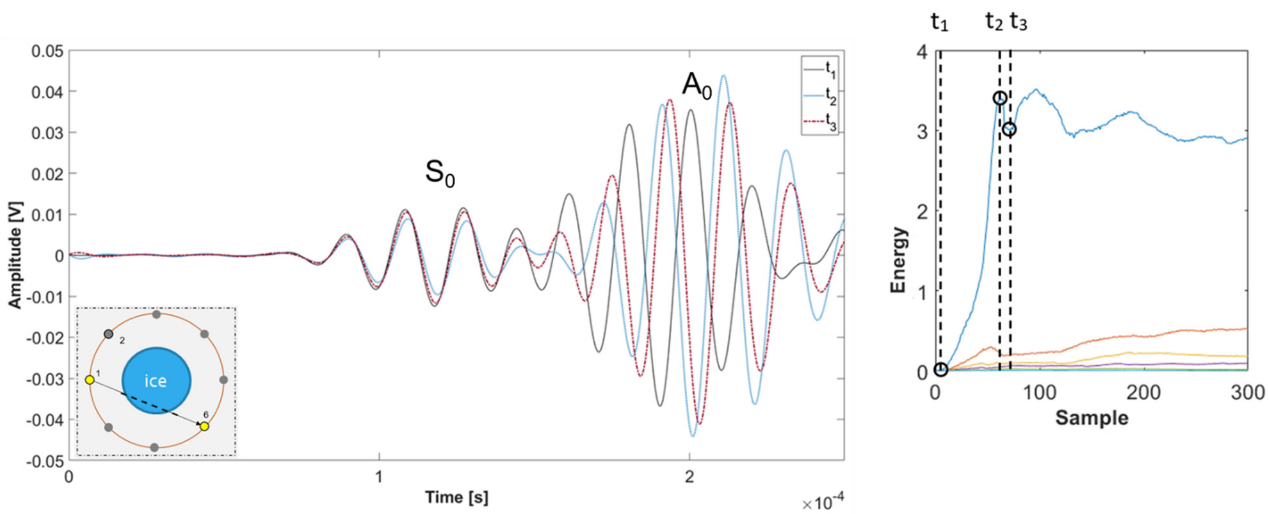

Figure 4 – Actual signals sensed by PZT 6 of C1, at different time instants ($t_1<t_2<t_3$).

A similar discussion arises when considering the other two couples. Looking at C2, the wave, excited by transducer PZT 1 and recorded by PZT 6, is plotted in Figure 4. Again, different time instants are considered.

First of all, based on the TOF assessment, it results that a fundamental symmetric mode, S_0, is travelling and then A_0 mode follows with greater amplitude as it is more tuned. As a consequence of the passage through the ice, the direct waves show some differences. S_0 results slightly affected with almost negligible amplitude variation and phase shift. Instead A_0 mode gets much slower when the ice defrosts while the amplitude first increases and then decreases. Meanwhile phase shift shows an increasing variation with a direct correlation to the defrosting level. This suggests TOF as a more suited feature than the energy of the difference signal for monitoring ice defrosting by using propagation through ice. However, this aspect requires further investigations to be confirmed.

Conclusions

A signal-based metric is introduced for guided wave feature extraction and specifically for the assessment of ice state. The data are described by using the energy of the difference signal (taking into account baseline and monitoring signals) as decision variable or state index. If such energy is mainly scattered from ice, highest sensitivity to ice melting is achieved when the lowest ultrasonic frequency is excited and the state index has a generally increasing trend. Conversely, when that energy is mostly transmitted through the ice, after an initial very steep increase, later the state index oscillates with a general decrease. Furthermore, the phase shift of signals, traveling through the frozen mass, is proportional to the defrosting level.

As a consequence of these findings, some future remarks can be outlined. The introduction of other state indicators [9,10] have to be contemplated, such as the TOF, more suited to follow phase changes that characterize especially the transmission through a frozen mass. The numerical modeling should be taken into account to aid physical interpretation of complex phenomena. In the current framework, it would allow both modeling a state change (solid to liquid), which locally alters the molecular structure and the mechanical behavior of the waveguide, and introducing variations in thickness of this latter. Finally, the reliability in the ice state assessment by the introduced metric have to be investigated further, in order to contribute to the development of an ultrasound-based ice control system, which would be fundamental to execute efficiently de-icing actions [13] or to establish the operating time of ice countermeasures.

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