Towards early ice detection on wind turbine blades using acoustic waves

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ABSTRACT

The study focuses on the early detection of ice using controlled acoustic waves propagating in the wind turbine blades. An experimental set-up with a cold climate chamber, a composite test object used in turbine blades and equipment for glaze and rime ice production has been developed. Controlled acoustic waves are generated by magnetostrictive Terfenol-D based actuator. The propagation of three orthogonally polarized acoustic waves was studied by means of 6 accelerometers positioned, 3 each, in 2 holders on the 8 m long composite test object. The results show that for the considered composite test object the formation of ice, the ice mass, icing areas and the temperature have a significant influence on controlled acoustic waves propagation w.r.t. Fourier transform, amplitude attenuation and RMS values as indicators concluding that the proposed acoustic wave technique is a promising approach for ice detection.

Keywords: Ice detection, controlled acoustic waves, composite material, rotor blade, wind turbine, magnetostrictive actuator

1. INTRODUCTION

The output of the wind turbine is strongly influenced by the environment. In places with a cold climate wind turbines are affected by icing. Icing is one of the main contributes to the low performance of the wind turbine. Even a thin layer of ice can strongly influence the boundary layers at the surface of the turbine blade and decrease the lift coefficient and increase the drag coefficient considerably[1]. Due to these factors the wind turbine can lose power. In fact according to simple propeller theory the power loss will be directly proportional to the change in lift and drag coefficients if their relative changes are the same. However, since the drag coefficient is more strongly influenced the situation is much worse in practice.

Somewhat greater ice layers can cause unbalance and influence the life time of bearings in various places of a wind turbine. Big chunks of ice can become loose and thrown away long distances and constitute hazard to lives for humans and animals. Really great ice buildup can of course wreck the entire wind turbine installation in a short time. In very rare cases the ice can even build a slat on the blade's leading edge. This is a high lift devise (usually combined with a slot) used on aircraft wings in order to increase the lift. Hereby the wind turbine can, by utilizing the higher lift, produce more energy than it was designed for and several types of difficulties can arise dependent on the control system.

It is possible to use a deicing system but both starting deicing to late and too early can turn out to be costly. The later fact is related to the detrimental influence on the construction material in the blades due to some methods of deicing and the cost of deicing itself. A sensor system applied to the blades of the turbine could detect ice and start a deicing system before power losses are already measured on the output of the generator. A sensor system can be built on different principles such as optical, acoustical, others. A review on ice detection sensors and others ice related issues for wind turbines can be found in [2-4].

Acoustic waves have been used in nondestructive testing of isotropic materials since a long time. In this area one is usually looking for defects, cracks etc. Originally these studies were made using bulk waves. Later in order to study slender bodies one has started using guided waves (which can be seen as a sum of bulk waves)[5,6]. An example of such

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a study can be found in[7] where guided waves have been used to detect deposits in tubings even beyond bends. The study of strongly anisotropic media is not so well developed and fundamental questions about what to measure remains to be answered[8].

Acoustic waves in solids have three different orthogonal polarizations. For isotropic materials and from physical principles as well as mathematical properties the polarizations can be separated into: longitudinal which means along the wave propagation, and two - mutually orthogonal - orthogonal to the wave propagation. Usually this partition is called pressure waves and shear waves. These two kinds of waves fulfill their own separate equations of motion. However the sum of the two solutions has to fulfill the boundary conditions. For fluids, lacking viscosity, there is only a pressure wave. Wind turbine blades are slender structures built on fiber glass and vinylester or epoxy leading to an anisotropic material. Some blades are of sandwich construction. From acoustic point of view the blades can be seen as waveguides for acoustic waves. This means that an acoustic bulk wave which starts in the blade will soon establish specific wave modes determined by both the wave equation and boundary conditions. Such wave guides have been studied since a long time and analytical results can be found for a homogeneous isotropic plate with rectangular cross section in[5]. Similar results for a plate with orthotropic anisotropy (i.e. it has 6 elastic coefficients) can be found in[9,10]. Such algebraic analytical results as for the plate one should not hope for in the case of a wind turbine blade. The finite element method can give numerical results related to the wave propagation for more complicated shapes. However, without numerical results from computations, we will still be able to measure acoustical modes and also eigenfrequencies for the blade. The specific wave modes have to be started in a specific but in advance unknown way. Some modes can be dispersion free which means that the group velocity is independent of the frequency. This facilitates the measurements because waves with different frequencies don’t catch up with each other and mix. However, different polarization states will mix due to the anisotropy.

In this paper several results of experimental study of acoustic wave propagation in composite structure with the focus on early ice detection are presented. The analysis of propagation of three orthogonal polarized acoustic waves is considered in case of different input signals and icing conditions. The results show that the formation of ice, the ice mass, icing areas and the temperature have a significant influence on guided wave propagation w.r.t. Fourier transform, amplitude attenuation and RMS values as indicators concluding that the proposed acoustic wave technique is a promising approach for ice detection.

2. METHOD

2.1 Cold climate lab with test set-up

In order to avoid complications by using a real turbine blade we choose to use a composite plate with rectangular cross section made of glass fiber and vinylester. This material is used to manufacture rotor blades of wind turbines.
There is reason to believe that the propagation of elastic waves in our test object will be influenced by ice on a surface, see, e.g.[11]. The following measurements have been made in Cold Climate Lab (Fig. 1).

1. Measuring the amplitude of the wave after propagating along the test object with ice on, using the same polarization as the exciting one.

2. Similar to 1 above but measuring another polarization than the exciting one.

3. Measuring the amplitude of the wave reflected by the section of the test object with ice on, using the same polarization as the exciting one.

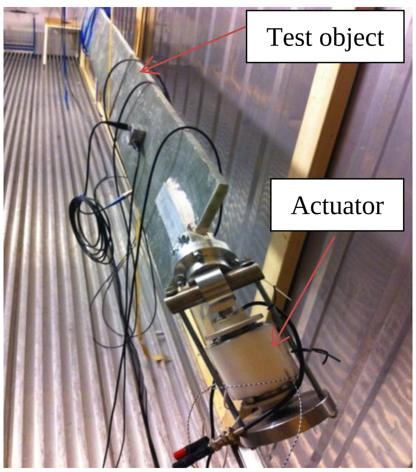
4. Similar to 3 above but measuring another polarization than the exciting one. (The reflected wave can contain all three polarizations.)

The above measurements have been made and compared with the similar situation without ice on but with a similar temperature on the test object.

Measuring amplitudes is based on the idea that the deposit of ice on the test object will couple the wave propagation in the two media via the boundary condition and herby change the amplitude. One idea using the different polarizations is the possibility to discriminate between different deposits on the test object because of the different boundary conditions they might set up. For example water will have a boundary condition coupling normal forces but not tangential forces whereas ice will couple both types of boundary conditions. The mixing of the three polarization states due to the anisotropy makes it difficult to interpret the experimental data


Cold Climate Lab


Data gathering and procession



Test object with actuator


Sensors on test object

Figure 1. Cold Climate Lab with test set-up.

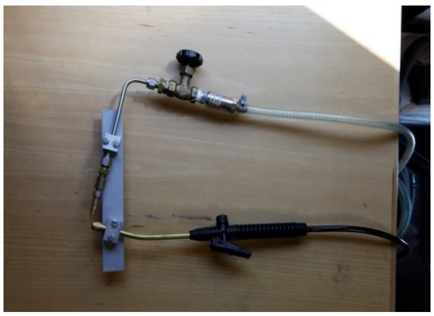
2.2 Ice manufacturing

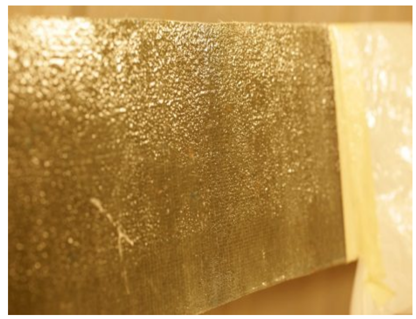
For the manufacturing of ice two different devices were developed and used (Fig 2.). One utilizing what is called exterior mixing of water and air with one nozzle for water and another for compressed air. The water and air flow can be separately adjusted. Another device utilizing what is called interior mixing of water and air using an adjustable (with compressed air) needle in the nozzle was also manufactured. Here the water and air flow can also be separately adjusted. The principle used in both devices is that the compressed air will split up the water in small droplets. These will freeze under subzero condition in the freezing room.

In order to produce glaze ice the droplets have to freeze on the test object. The water temperature can be as high as about + 15 ^{o}C. Ordinary gardening equipment for spraying pesticides is sufficient for the water supply. Compressed air and a simple air nozzle will help to make smaller droplets and spread them out. The temperature in the freezing room should be about - 5 ^{o}C. If it is higher the ice might melt, because of the relatively high temperature of the droplets, and it will be difficult to control the thickness of the ice layer. There is no need to pre cool the water which could produce another problem by clogging the water lines. The equipment is essentially used as a spray gun for painting producing a crosswise pattern.

However in order to produce rime ice the droplets have to freeze before they reach the test object. Somewhat higher demands than above is put on water and air nozzles. This is because of the need to make fairly small droplets. In nature small water droplets can obtain as low temperature as – 40 ^{o}C without freezing. The temperature in the freezing room should be about - 10 ^{o}C or lower. There is no simple way to tell exact dimensions of the equipment, pressure of liquids and temperature needed for producing rime ice. The rime ice is sprayed like the glaze ice but the difficulties in producing well defined layers of rime ice is much higher than for glaze ice.

It is difficult to spray ice layers with well-defined thickness and small surface irregularities. This makes the accuracy of the measurements of the thickness low. The thickness of the ice is measured with a (cold) caliper on ice flakes removed from the test object.





Device for manufacturing of glaze ice using separate nozzles for water and air. Glaze ice sample.

Device for manufacturing of rime ice using one nozzle and mixing of water and air inside. Rime ice sample.

Figure 2. Two different devices for the manufacturing of ice.

The pureness of the water can influence the freezing of the droplets. Less pure water gives higher freezing temperature. It can be of value to pre cool the water in the rime ice case. It can be of interest to notice that a glaze ice layer of about 1 mm can evaporate totally in a few days at - 5 ^{o}C . In practice the ice buildup on airfoils can take on many different shapes which from practical point of view are less interesting as long as small deviations from efficient operation of the wind turbine are concerned.

2.3 Generation of acoustic waves

The acoustic waves were generated by means of a magnetostrictive actuator using Terfenol-D. In[12-17] treatises on magnetostrictive devices can be found. Our type of transducer can only influence the surrounding along an axis. Thus it can only generate bulk waves with longitudinal polarization (along the axis of propagation). However these bulk waves will soon interact with the surface of the test object and by reflection give rice to the two orthogonal transversely polarized waves and set up wave guide modes. By varying the angles for the transducers axis relative the test object one can vary the amplitude of the three polarization states, see Fig. 1. We used the transducer with the axis angled at 45 ^{o} and

45 ° because this gave relatively high excitation of all three polarization states. Individual polarization states can be given higher excitation for other angles. However, due to the anisotropy it was almost impossible to produce pure polarization states.

The transducer can be used for three different types of actuations dependent on purpose. First, the transducer can be excited electrically by a voltage step in Labview (called excitation of type A). Due to inertia effects the magnetostrictive material will respond in a less sharp stepwise motion. From Fourier theory it is known that a unit step contains all frequencies but with much lower amplitude for higher frequencies. By using a frequency filtering technique in Labview one can extract the frequency of interest. Second, the transducer can be excited by sinusoidal electric voltage puls with, in Labview, specified frequency and amount of periods (called excitation of type B). As such puls will contain a wider frequency spectrum than wanted the same kind of filtering technique as above has to be utilized. Here again inertia effects of the magnetostrictive material will influence and can give more periods than specified electrically. Because of the usage of filtering technique this does not influence the results. However another consequence of the inertia effect is the rapidly reduced amplitude, in the mechanical waves produced, with higher frequencies. Third, the transducer can be excited electrically with a sinusoidal electric voltage signal with, in Labview, specified frequency and "infinite" length (time wise), (called excitation of type C). Note, that only the excitations A and B can be used to study the group velocity for the waves. Our Terfenol-D actuator was useful up to about 9000 Hz due to the reasons above.

2.4 Measurement and data acquisition system

In order to measure the acceleration of the displacements due to the acoustic waves piezoelectric transducers of the type IMI608A11 were used with coaxial cables RG58. They were mounted in a parallelepiped of aluminum in an orthogonal way according to Fig. 1, (Sensors on test object). After actuation by the Terfenol-D transducer the electric signal from the first accelerometer on the test object was again filtered and used for the various propagation experiments.

The central unit was the PC with the Labview and Matlab programs. This unit controls the signal to the Terfenol-D transducer which was amplified with a HiFi amplifier. The cables from the accelerometers were coupled to an analog digital converter which in turn was coupled to the PC. We also used an oscilloscope, Agilent Technologies DSO1014A, monitoring the analog signals and capable of sending digitalized data to the PC.

3. DATA, ANALYSIS, RESULTS

The sketch of the experimental set-up is depicted in Fig. 3.

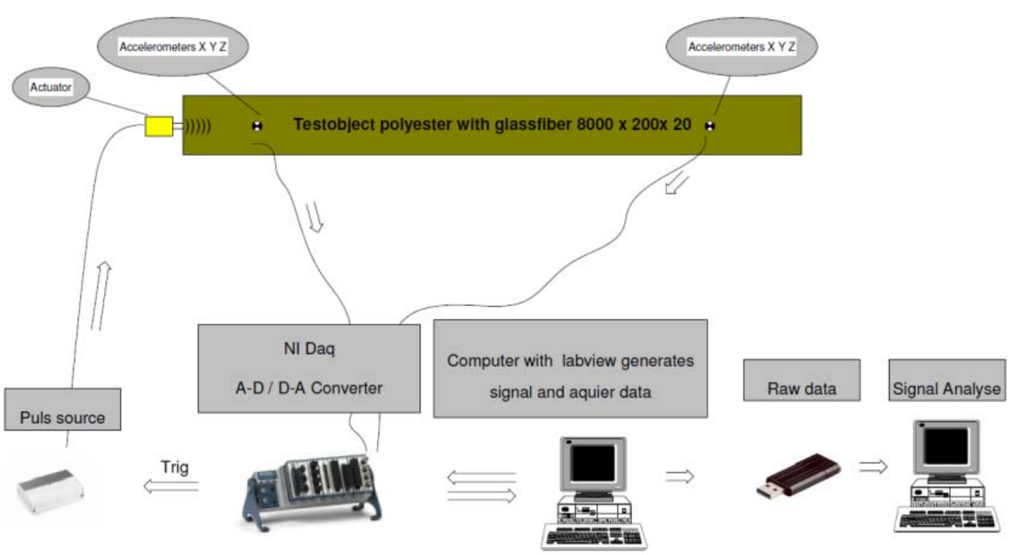


Figure 3. Sketch of the experimental set-up in Cold Climate Lab.

The experiments have been performed on a plate with rectangular cross section with dimensions 800cm x 20cm x 2cm made of glass fiber and vinylester, see Fig. 1, (Test object with actuator), with variation of the type of excitation inputs, placement of actuator, temperature and icing conditions. Namely, three types of Terfenol-D actuator excitation inputs have been used: pulse-like, sinus-like and continuous sinus-like. Icing of the test object has been varied with respect to type of ice (glaze ice, rime ice), icing area and its location, and thickness of ice (mass of ice).
The measurement data has been recorded for vertical, horizontal and longitudinal polarizations by sensors located before icing area and after icing area of the test object. Different testing strategies and indicators (indexes) can be used to indicate ice formation, see e.g.[2,11,18-22]. In our study three indexes have been used for analyzing the data obtained and indicating of ice: Fast Fourier Transform (FFT), amplitude attenuation and relative difference in root mean square (RMS) of the acoustic signal propagated in the test object without ice and acoustic signal propagated in the test object with ice.

In the Fig. 4 - 8 the results of FFT and amplitude attenuations signal analysis have been presented for vertical, horizontal and longitudinal acoustic wave polarizations. First the test object is without ice, and then it is covered with glaze ice under different icing conditions (ice thickness and icing area). External Terfenol-D actuator excitation is pulse-like. The mass of glaze ice covered the test object was determined by using the values of glaze ice area, thickness of ice and volumetric density of glaze ice[11].

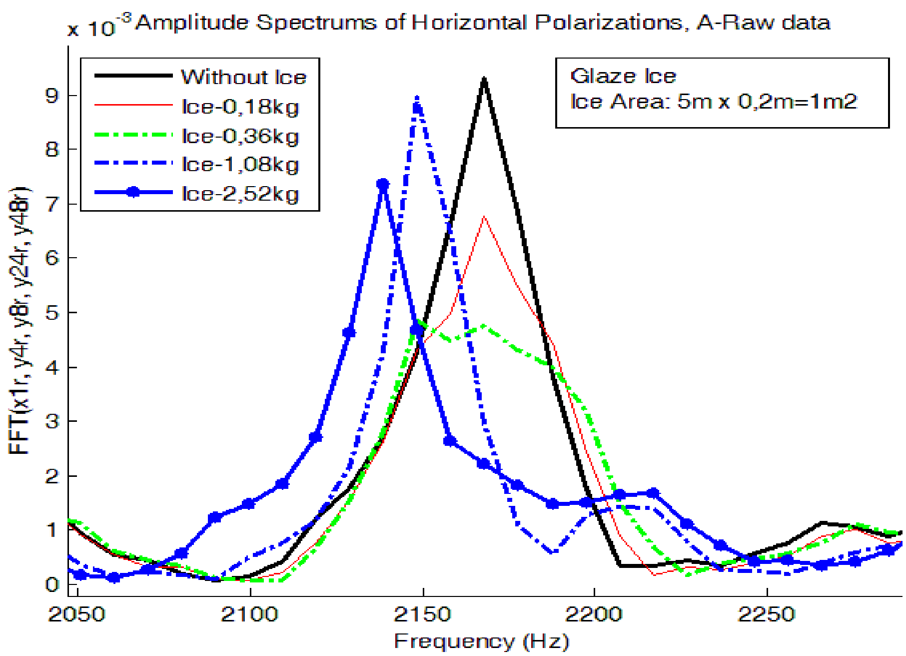


Figure 4. Fast Fourier Transform (FFT) for horizontal polarizations (Glaze ice).

Fig. 4 and 5 show the amplitude spectrums of horizontal and vertical wave polarizations, respectively. The solid black lines are for the polarizations in the test object without ice. All others lines are for the wave polarizations in the test object with different amount of glaze ice (m_{ice}=0,18kg; 0,36kg; 1,08kg; 2,52kg). The analysis of these curves clear indicate differences between amplitude spectrums and phases of the wave polarizations obtained for the test object with ice and the respective data for the test object without ice.

Fig. 6 and 7 show the amplitudes of vertical and longitudinal wave polarizations, respectively. The solid black lines are for the polarizations in the test object without ice. All others lines are for the wave polarizations in the test object with different amount of glaze ice (m_{ice}=0,18kg; 0,36kg; 1,08kg; 2,52kg). The analysis of these curves clear indicates amplitude attenuation and phase shift for the curves corresponding to the wave polarizations obtained for the test object with ice.

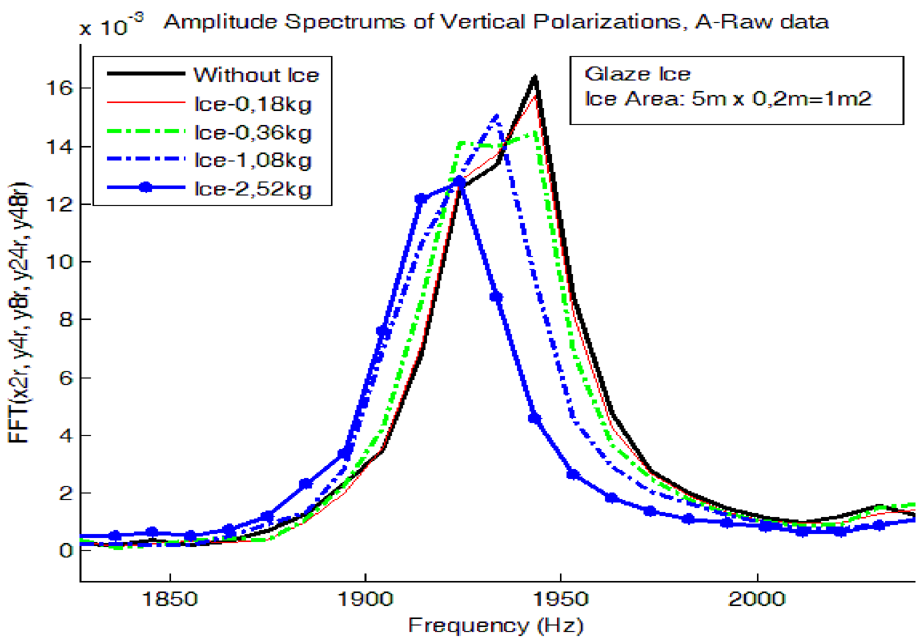


Figure 5. FFT for vertical polarizations (Glaze ice).

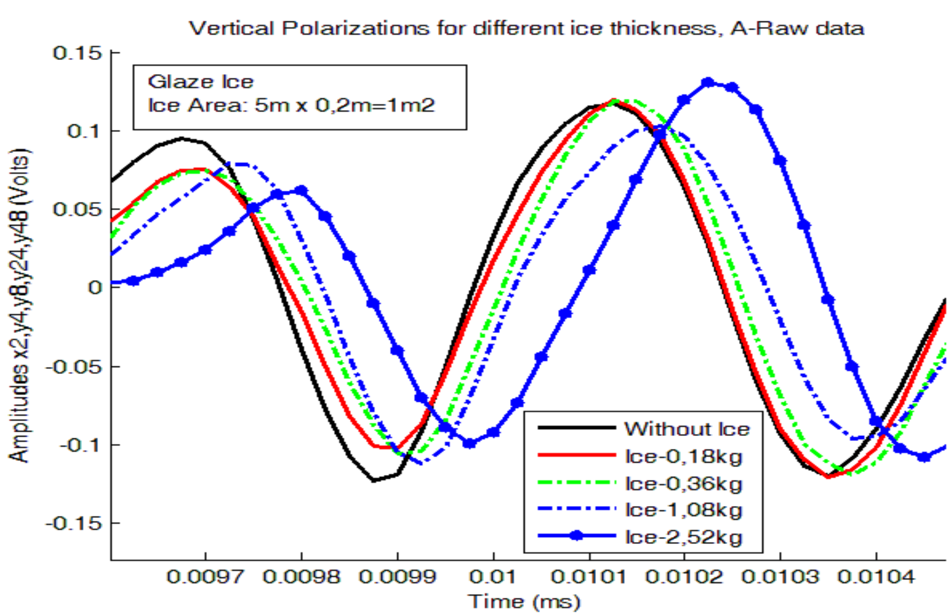


Figure 6. Amplitude of vertical polarizations (Glaze ice).

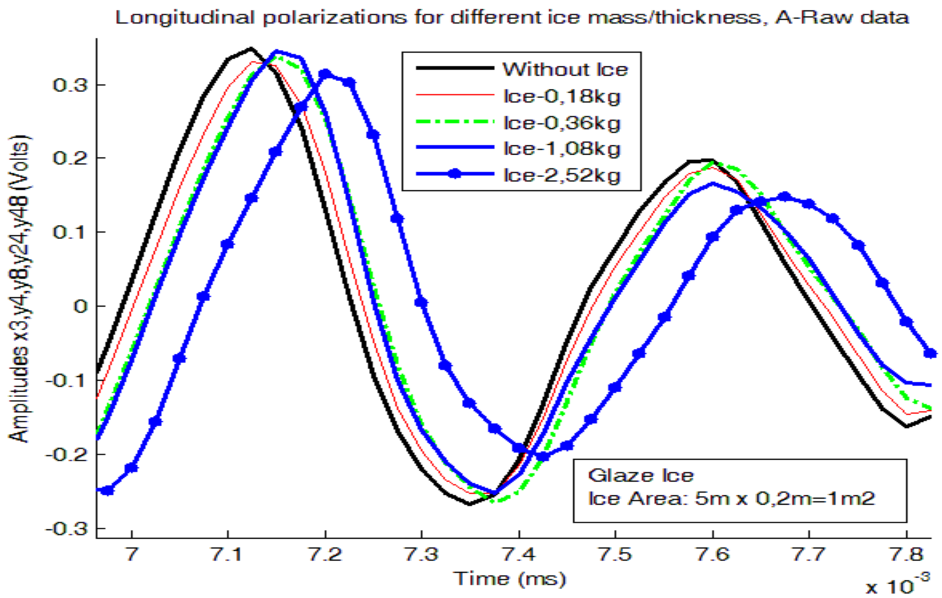


Figure 7. Amplitude of longitudinal polarizations (Glaze ice).

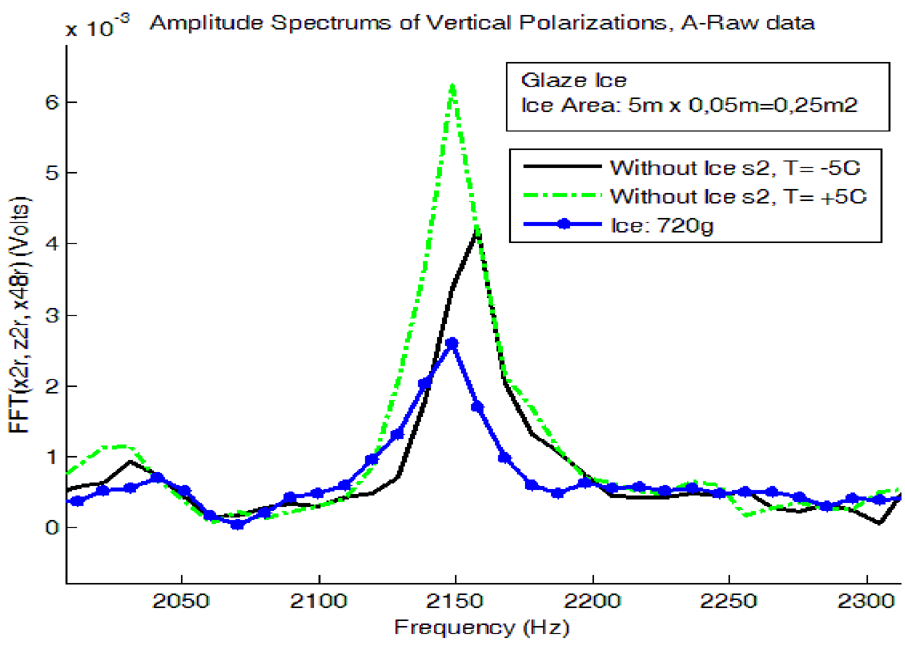


Figure 8. FFT of vertical polarizations (Glaze ice).

In Fig. 9-10 some results obtained are presented for the test object under rime ice conditions, different temperature and pulse-like external excitation. The mass of rime ice covered the test object was determined by using the values of rime ice area, thickness of ice and volumetric density of rime ice[11].

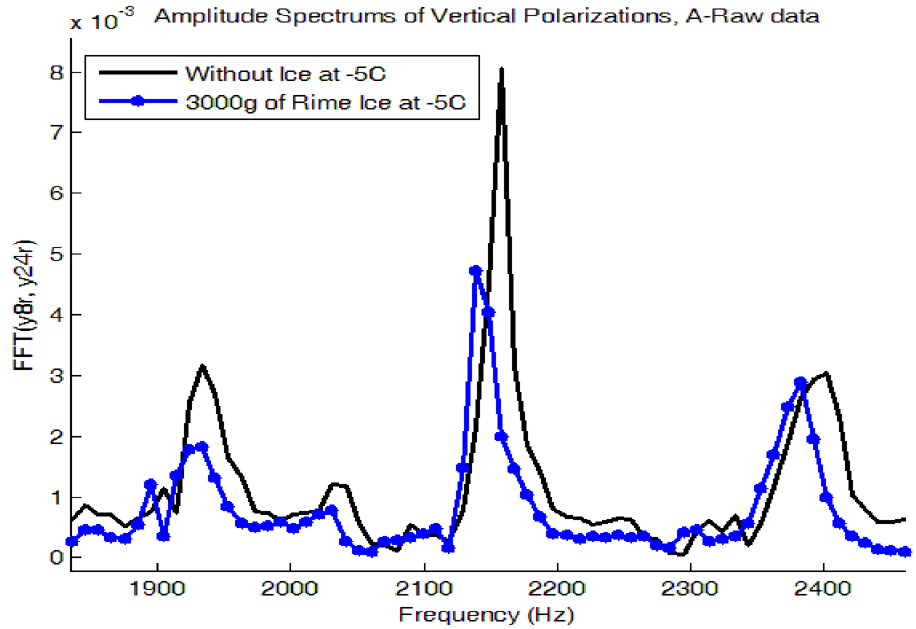


Figure 9. FFT of vertical polarizations (Rime ice).

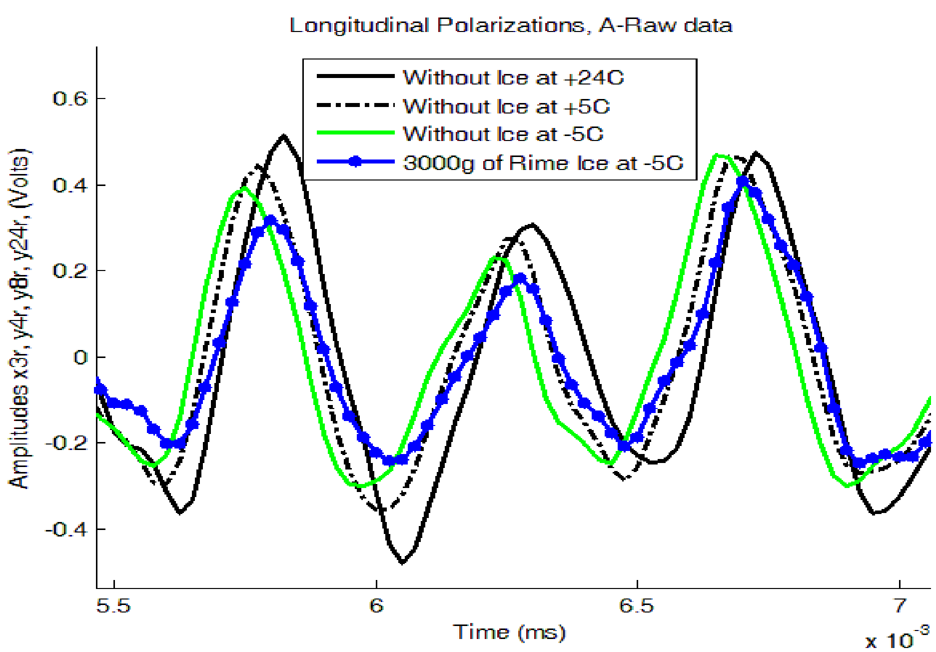


Figure. 10 Amplitude of longitudinal polarizations (Rime ice).

In Table 1 some of the results are presented obtained by evaluation of the relative differences in RMS and $(RMS)^2$ of the acoustic signal in horizontal polarization in the test object without ice and acoustic signal propagated in the test object with different amount of glaze ice (m_{ice}=0,18kg; 0,36kg; 2,52kg). It is clear that the icing of the test object significantly decreases the RMS and $(RMS)^2$ values for the wave polarizations.

Table 1. Relative difference in RMS of the acoustic signals.

Type A, Ice area= 5mx0,2m=1m2, Horizontal Polarization x1, dRMS, d2RMS

Ice mass, kg	**0,18**	**0,36**	**2,52**
Raw data dRMS, %	11,3	13,9	19,7
Raw data d2RMS, %	21,3	25,8	35,6
Filtered data dRMS, %	11,4	14,5	14,8
Filtered data d2RMS, %	21,6	26,9	27,3

$$dRMS = 100 * (RMSx1 - RMSy) / RMSx1$$
$$d2RMS = 100 * ((RMSx1)^2 - (RMSy)^2) / (RMSx1)^2 \qquad (1)$$

Here in Table 1 and in equations (1) *x1* is a signal propagated in the test object without ice and *y* is the signal propagated in the test object with ice.

4. CONCLUSIONS

The paper presents a demonstrator for the ice detection system based on controlled acoustic waves, magnetostrictive actuator and accelerometers. An experimental set-up with the demonstrator in Cold Climate Lab, composite test object and equipment for glaze and rime ice production has been developed. The composite material in the test object is the same as normally used in wind turbine blades. LabVIEW and DAQ system from National Instruments are used for measurement data gathering and processing. The propagation of three orthogonally polarized acoustic waves was studied for different scenarios of icing of the test object and different excitations obtained by Terfenol-D based actuator. Data was measured by means of 6 accelerometers positioned, 3 each, in 2 holders on the 8 m long composite test object. Fast Fourier Transform, amplitude attenuation and RMS values are used as indicators for ice formation and numerical algorithm has been developed to analyze the measurement data. Analysis of the results obtained (see Fig. 4-10, and Table 1) show that the formation of ice, the ice mass, icing areas and the temperature have a significant influence on guided wave propagation w.r.t. Fourier transform, amplitude attenuation and RMS values. It was also shown that there is no significant damping in the material that has been tested. The results obtained give possibility to conclude that the proposed ice detection system based on controlled acoustic waves is a promising approach for ice detection.

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