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INVESTIGATING THE APPLICATION OF GUIDED WAVE PROPAGATION FOR ICE DETECTION ON COMPOSITE MATERIALS

Siavash Shoja*, Viktor Berbyuk, Anders Boström

Applied Mechanics, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden
{siavash.shoja,viktor.berbyuk,anders.bostrom}@chalmers.se

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Abstract. *Wind turbines operating in cold regions face icing problems. At the same time these regions are one of the best places to install the wind turbines. To minimize this problem and optimize the de-icing system it is very important to have an efficient ice detection system. Application of guided wave propagation has been previously considered in aircraft industries. To study this application for wind turbines, guided wave propagation should be investigated in composite materials. In the current work, first the guided wave propagation in multi-layered anisotropic materials is mathematically modelled and dispersion curves were obtained. Moreover the composite plate was homogenized to an anisotropic plate in order to simplify the calculations. Comparison of dispersion curves shows changes in group velocity when a second layer as ice is added on top of the first layer. Next, a finite element model was made to observe the effects of ice accretion on top of a composite plate. An experimental set-up was also developed at a cold climate lab on a composite test object used in wind turbine industry. The guided wave propagation was studied experimentally to see the effect of temperature and ice on the material and measurement data was obtained to validate the computational model. Both numerical and experimental results show that a patch of ice on top of a composite plate reflects the propagated guided waves with an amplitude that raises by increasing the thickness of the ice layer. Furthermore, ice accumulation affects the group velocity of the guided waves and it proves that the use of guided waves is a promising method to detect ice on turbine blades.*

1 INTRODUCTION

Some of the best sites to install wind turbines are located at higher altitudes or in cold regions. Wind speed increases approximately by 0.1 m/s each 100 m of altitude for the first 1000 m [1]. Moreover, wind turbines operating in cold regions have higher potential of wind power due to higher air density and consequently higher wind kinetic energy [2].

One of the biggest obstacles which prevents the wind farms to be set up in these regions is icing problems. Previous studies show that ice accumulation on wind turbine blades influences the power production [3, 4]. Accretion of ice on the blades reshape the blade airfoil. Virk *at al.* [5] found a significant change in the flow behavior and aerodynamic characteristics of the blades which leads to considerable power loss. Additionally, increasing ice accretion on the blades causes mechanical failure due to higher load on the blades, electrical failure, measurement error and safety hazard due to ice throw [1, 6]. In order to optimize the de-icing system of the wind turbines it is important to know the location of ice, amount of it and type of it. This information can be gained using an efficient ice detection method.

Homola *et al.* [7] and Parent *et al.* [1] made comprehensive reviews on the available methods of ice detection. Generally the methods can be divided into two groups of in-direct and direct methods. The direct methods detect some parameter which changes by accretion of ice such as mass, wave velocity, reflective properties etc. In the in-direct methods, the measurement is based on either the weather conditions which lead to icing problems or measuring the effect of icing such as reductions in power production. The above reviews show that all of the available ice detection methods have pronounced disadvantages and are not highly efficient. However, using ultrasonic guided wave approach is one of the most promising ones applicable to wind turbines [7].

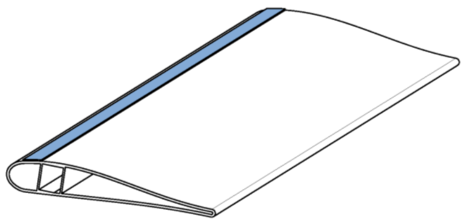
Application of guided wave propagation for ice detection on aircraft wings has been previously introduced. Chamuel [8] has proposed and designed a detection system by monitoring variations in flexural waves transmitted through the outer surface of an aircraft airfoil. A somewhat similar system was proposed by Luukkala [9]. In his work a device was designed and used to collect the water on the wing and continuously examine it using ultrasonic waves to find out if ice is built. Liu *et al.* [10] used two types of ultrasonic transducers on the inner part of an aircraft wing skin to monitor the ice build-up by measuring the thickness. Using this technique they could measure the thickness of ice in the range of 1 mm to 1.5 mm on a 3 mm aluminum plate. Gao and Rose [11] proposed a new model based on the analysis of guided-wave propagation in multi-layered structures to detect the ice. Using the model they could detect thickness and type of ice accumulated on an aluminum plate. They also evaluated the method using a sample experiment.

More studies have been done on de-icing models using ultrasonic waves in which it has been tried to use the shear force due to wave propagation to remove the ice from the surface of the plates [12-14, 6].

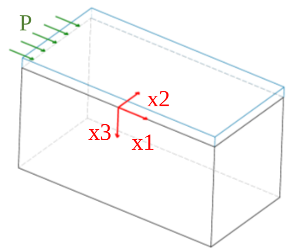
The current work is focused on using guided waves in order to detect the ice on a composite plate which has applications on wind turbines. First a mathematical model is proposed to analyze the guided wave propagation in multi-layers. The multi-layer structure consists of two layers where the first one is an anisotropic material representing the composite plate and the second layer is an isotropic material representing the ice. Next, the composite plate is simplified by a homogenization model in order to be able to build a FE model and the numerical results are presented. Finally an experimental set-up was developed and changes in the output signal are presented in different scenarios.

2 THEORY

The skin of wind turbine blades is mainly made of composite materials and its thickness varies depending on size and type of the turbine. The surface has an airfoil shape and has curvature, however, in a selected region along the blade it can be considered as a flat plate. Since in our model the wavelength of the guided wave is much larger than the thickness of the plies, the composite plate is considered as a homogenous and anisotropic material. At the beginning of ice accretion on the blade, it follows the shape of the blade. In this case, ice can also be modelled as a flat plate and by neglecting its microstructure, it can be modeled as a homogenous and isotropic material.



(a)



(b)

Figure 1: (a) Schematic view of a piece of turbine blade and accumulated ice; (b) 3D view of a 2-layered model.

2.1 Wave mechanics

Wave propagation in multilayers has been investigated by the transfer matrix method [15, 16]. In this method propagation equations are built in a matrix form for an arbitrary number of layers. The solution of each layer is connected to the next one by applying the continuity conditions. This method is used for multilayered anisotropic materials by Nayfeh [17, 18] and different scenarios were considered later on for different combinations of isotropic and anisotropic layers [19]. The problem is solved here for this specific case.

The displacement of the wave field in each layer can be obtained by applying Hooke's law and deriving the equation of motion:

$$\rho^{(n)}\ddot{u}_i = C_{ijkl}^{(n)}\frac{\partial^2 u_l}{\partial x_j\,\partial x_k} \qquad n = (1,2) \tag{1}$$

Here n is the number of each layer, ρ is the density and C is the stiffness matrix. To solve the equation, the displacement is assumed in the form

$$u_i^{(n)} = U_i e^{i(k_m x_m - \omega t)} \tag{2}$$

where k_m is the wave number and ω is the angular frequency. Since the material changes in the vertical direction from the first material to the second one, k_3 becomes a function of thickness. By using Eq. (2) and Eq. (1) the following Christofel equation is obtained

$$\left(\Gamma_{im}^{(n)} - \rho^{(n)}\omega^2\delta_{im}\right)\{U_m\} = 0 \tag{3}$$

Here

$$\Gamma_{im} = C_{iklm}k_k k_l \tag{4}$$

For a nontrivial solution, the determinant of the coefficient matrix in Eq. (3) has to be set equal to zero:

$$\left|\Gamma_{im}^{(n)} - \rho^{(n)}\omega^2\delta_{im}\right| = 0 \tag{5}$$

Since the problem is going to be solved in 2D, U_2, x_2 and k_2 are removed from the equations. By solving Eq. (5) for k_3, four solutions will be obtained in each layer where each solution is a function of k_1 (wave-number in the direction of propagation) and ω. By rewriting Eq. (3) based on the obtained results for k_3 it is possible to make the equation only depending on k_1 and ω. Eqs. (6) to (9) are obtained for displacement and stress by summing up all the results.

$$U_1^{(n)} = \sum_{j=1}^{4} B_{1j}^{(n)} U_{1j}^{(n)} e^{i(k_1 x_1 + k_{3j}^{(n)} x_3 - \omega t)} \tag{6}$$

$$U_3^{(n)} = \sum_{j=1}^{4} B_{3j}^{(n)} U_{3j}^{(n)} e^{i(k_1 x_1 + k_{3j}^{(n)} x_3 - \omega t)} \tag{7}$$

$$\sigma_{33}^{(n)} = \sum_{j=1}^{4} i k_1 D_{1j} U_{1j} e^{i(k_1 x_1 + k_{3j}^{(n)} x_3 - \omega t)} \tag{8}$$

$$\sigma_{13}^{(n)} = \sum_{j=1}^{4} i k_1 D_{3j} U_{1j} e^{i(k_1 x_1 + k_{3j}^{(n)} x_3 - \omega t)} \tag{9}$$

Here B_1, B_3, D_1 and D_3 are constants which should be found later. Next, by applying the boundary conditions (BCs) it is possible to create the transformation matrix in the Eq. (10). The BCs are continuity of stress and displacement between the two layers and zero stress and traction in top and bottom free surfaces (Figure 2).

$$\begin{bmatrix} A_{11} & \cdots & A_{18} \\ \vdots & \ddots & \vdots \\ A_{81} & \cdots & A_{88} \end{bmatrix} \begin{Bmatrix} B_1^{(1)} \\ \vdots \\ D_3^{(2)} \end{Bmatrix} = 0 \tag{10}$$

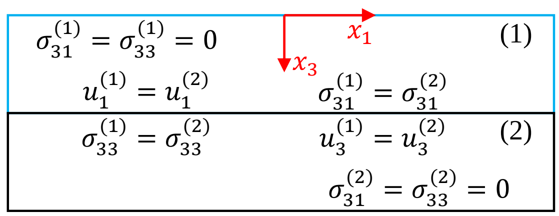


Figure 2: 2D model of the layers with appropriate BCs.

The matrix A is a function of k_1 and ω and for nontrivial solution, the determinant of the coefficients has to set equal to zero which makes the dispersion relation.

$$|A(k_1, \omega)| = 0 \tag{11}$$

Solving the dispersion equation includes numerical difficulties. Garcia *et al* [20] introduced a new method to create the dispersion curves using Floquet-Bloch theory in a unite cell and solve it by finite elements. In this study, their method is first evaluated in one case and then used to create the dispersion curves in other scenarios.

2.2 Homogenization of material

One method to investigate the propagation of guided waves in composite structures is to calculate equivalent stiffness properties for the structure and consider it as one layer of anisotropic material. Here a plate theory can be used. Classical laminate plate theory neglects shear deformations. To include the shear forces, other theories such as first order shear deformation theory (FSDT) or higher order shear deformation theory have been introduced. It has been shown that FSDT gives good accuracy in wave propagation problems, however, the results depends on shear correction factor and plate thickness [21].

The material used in this study is a 20 mm thick composite plate with 62 layups. To investigate the validity of using FSDT to homogenize the material, first the equations for dispersion curves were solved for a multilayered geometry with 62 layers and the results have been compared with the dispersion curves in a homogenized plate with the same thickness. Figure 3 shows that reasonable results are obtained for the frequencies lower than 0.7 kHz m for the first 3 modes (the green zone) which means it is possible to use this method for further calculations.

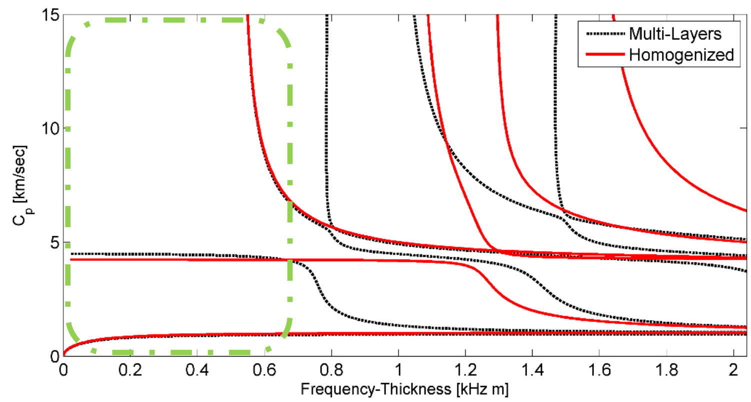
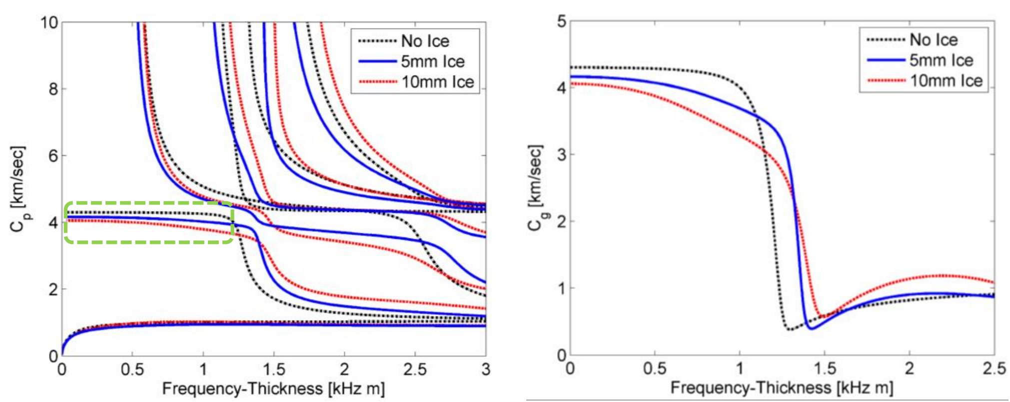


Figure 3: Comparison of dispersion curves obtained for multilayered structure versus a homogenized plate.

2.3 Effect of ice layer on dispersion curves

To make a rough estimation about the possibility of ice detection using guided waves, dispersion curves were obtained for two layers of homogenized composite plate and a layer of ice. As mentioned, ice is modeled as an isotropic material and properties are taken from the literature [22]. Figure 4 shows the results for a 20 mm composite plate in 3 scenarios of no-ice, 5mm ice and 10mm ice.



(a) (b)

Figure 4: Comparison of dispersion curves for no ice on the plate, 5mm ice and 10mm ice on the plate (a) Phase velocity versus frequency (b) group velocity versus frequency for symmetric modes.

Changes due to accretion of ice is negligible in the first mode, but it is significant in the second and higher modes. The green zone in Figure 4 shows the best possible frequencies which make significant change in phase velocity during ice accumulation.

3 NUMERICAL MODEL

The numerical study is performed by creating a 2D FE model and applying the excitation on one side. The geometry is a 20 mm by 8 m rectangle as the composite plate and a rectangle as ice with 1m length and different sizes for the thickness. The second layer is located between 4 m and 5 m length from the excitation side of the plate. Wave is applied as a windowed sinus wave with 5 kHz center frequency and it is detected at 2 m and 6 m from the excitation side. Figure 5 shows the schematic view of the FE model.

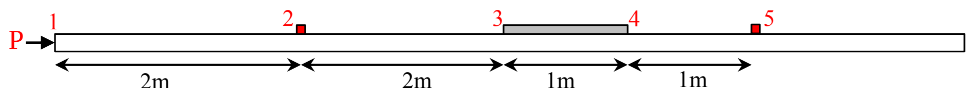


Figure 5: Schematic view of FE model.

Since the excitation is in the longitudinal direction, waves propagate as symmetric modes. However, when the wave reaches the second layer it creates reflections in both symmetric and asymmetric modes. The effect of reflection is visible in Figure 6 (Region I). The amplitude of reflections rises proportionally by increasing thickness of ice layer (Figure 7-a).

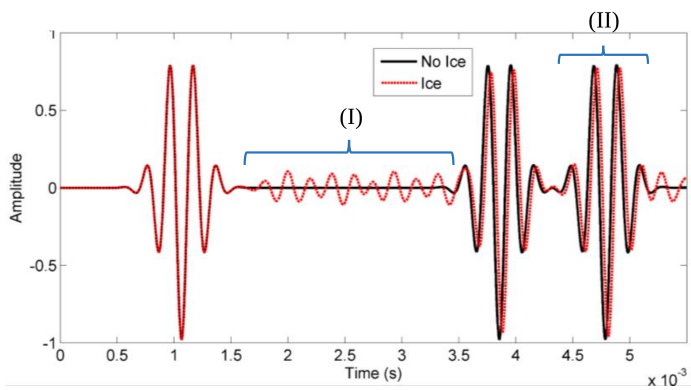


Figure 6: Comparison of the signal at the first detection point for a plate with and without ice.

The amplitude of the signal decreases after the wave propagates two times through the material when a layer of ice is added on the plate. Furthermore, a phase shift can be observed in the signal which is due to change in group velocity. Figure 7-b shows a comparison in this region for different thickness of the ice layer.

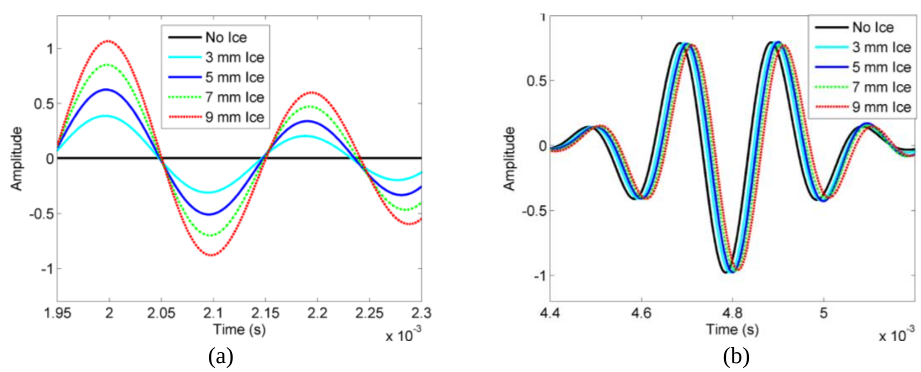


Figure 7: Comparison of the signal for different thickness of ice layer in (a) region I and (b) region II.

4 EXPERIMENTAL STUDY

The experimental setup was made in a cold climate lab on a composite plate with the dimensions of 0.02 × 0.2 × 8 m (Figure 8). The test object contains 62 layups of glass fiber and Vinylester which is a common material used in the wind turbine industry. The plate was excited from one side using a transducer in the longitudinal direction. The signal was detected at two points 2 m and 6 m from the excitation side using two accelerometers. The excitation signals are windowed sinus waves at the three frequencies 3, 5 and 7 kHz. More details about the experimental setup has been explained in previous work [23]. The effect of temperature and ice is investigated in this experimental work.

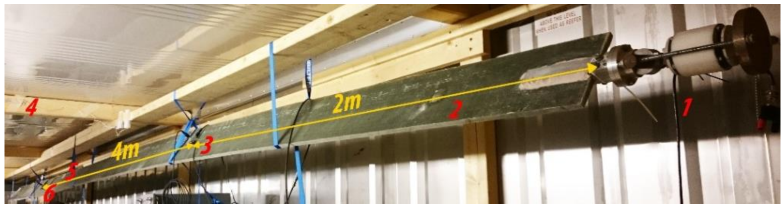
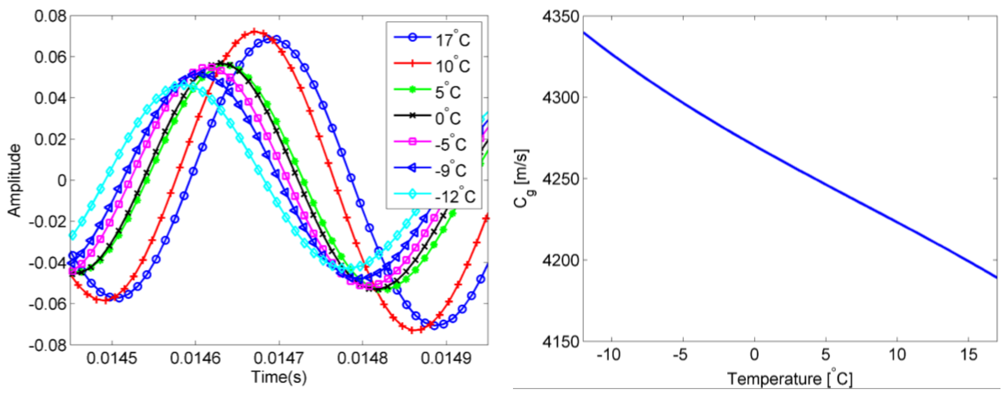


Figure 8: Experimental setup containing (1) transducer, (2) composite material, (3) first accelerometer, (4) thermometer for surrounding temperature, (5) thermometer for material temperature, (6) second accelerometer.

4.1 Effect of temperature

It is important to know how the behavior of the material changes at low temperatures when a wave is propagating through it. To investigate this characteristic the material was cooled down from the room temperature to -12 ºC and the signal was detected continuously.



(a) (b)

Figure 9: (a) Comparison of signal for different temperatures and (b) group velocity versus temperature

Results show that by decreasing the temperature, the amplitude of the signal is decreasing but the group velocity is increasing (Figure 9). These changes can be observed even between -9 ºC and -12 ºC. This is because Young's modulus of the resin is highly depended on temperature and lowering the temperature makes the composite more rigid.

4.2 Effect of ice accretion

The effects of ice accration was investigated by building ice on the plate. The method of manufacturing ice has been explained in previous work [23]. Here ice was built at -12 ºC and it is a mixture of glaze and rime ice and located between 4 m and 5 m from the excitation side.

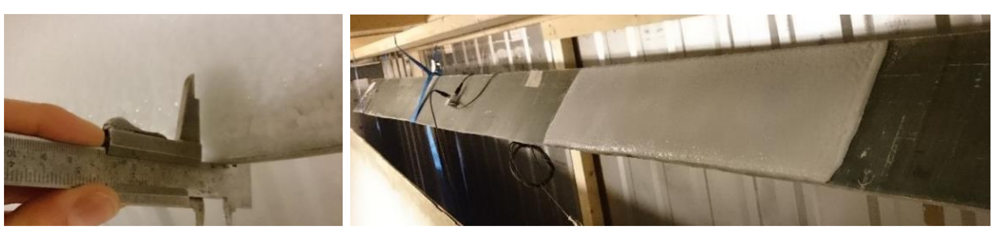


Figure 10: manufactured ice on the plate.

Changes of the signal due to icing conditions can be observed in two different regions (Figure 11), first when the signal reflects back to the first sensor from the ice layer which makes larger amplitude (I) and second when wave travels two times through the plate which lowers the amplitude and group velocity (II).

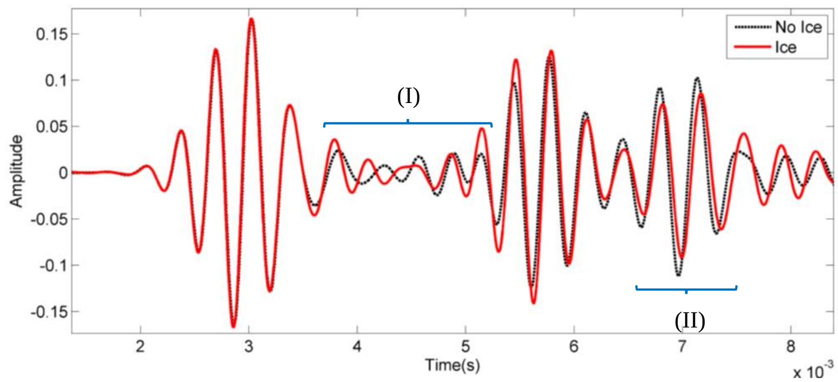


Figure 11: A-scan of the signal at the first accelerometer.

The changes of the signal can be observed further in Figure 12 for different ice thicknesses. Comparisons show that increasing the thickness of ice creates larger reflections (a) and lowers the amplitude and group velocity (b).

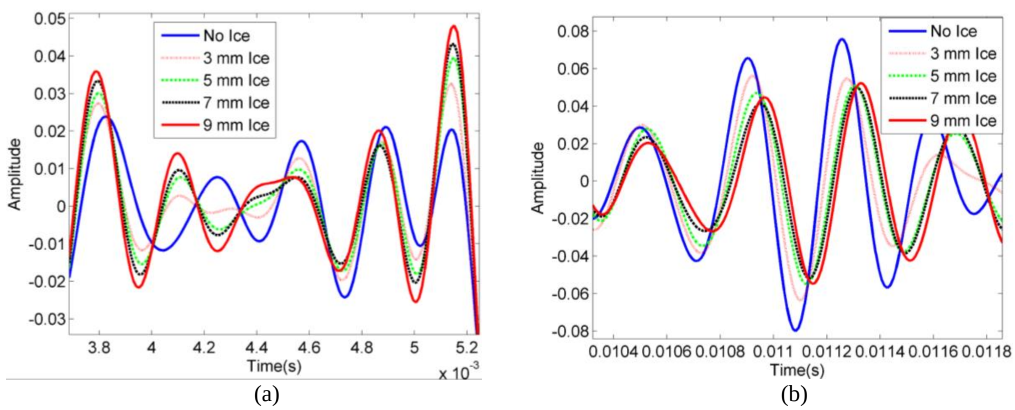


Figure 12: A-scan of the signal for different thicknesses of ice in (a) region I and (b) region II.

Finally by calculating the group velocity for different ice thicknesses, it is possible to see the changes due to icing on the material. Group velocity was calculated for three different excitation frequencies. The decrease in group velocity because of ice accretion is significant.

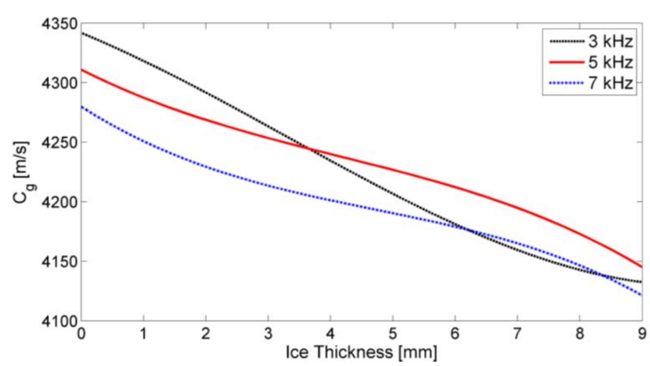


Figure 13: Group velocity versus ice thickness for different excitation frequencies.

5 CONCLUSIONS

Propagation of guided wave in composite materials has been investigated in this study in order to be able to detect a layer of ice on the plate. Studying the dispersion curves shows that FSDT can be used to approximate the composite plate with a homogeneous material for frequencies lower than 1.2 kHz m. Moreover, adding a second layer (ice) on top of the composite layer makes significant changes in phase and group velocity of symmetric modes in a specific frequency range.

A numerical model was also made to predict the results due to ice accretion and it shows that adding a second layer as ice on top of the first layer creates reflections, for which the amplitude raises by increasing the thickness of the ice layer. After the wave propagates two times through the material it is possible to see a decrease in amplitude and group velocity of the wave.

Significant dependency of the properties of the material on temperature was observed in the experimental work. It showed that group velocity of the wave raises by lowering the temperature. Ice was manufactured on top of the composite plate and the plate was excited at three different frequencies. It is possible to see that accretion of ice creates reflections and the amplitude of the reflected wave raises by increasing the ice thickness. Moreover, increasing the thickness of ice creates lower amplitude and lower group velocity of the wave. The group velocity decreases about 200 m/s when 10 mm ice is accumulated on the plate.

6 ACKNOWLEDGEMENTS

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