THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SOLID AND STRUCTURAL MECHANICS

Guided Wave Propagation in Composite Structures

Application to ice detection on wind turbine blades

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Waterfall plot of acceleration in computational model after icing condition.

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Abstract

Guided waves are an efficient non-destructive tool in inspection and fault detection of elongated structures. Due to the special characteristics of composite materials, study of guided wave propagation in them has been an interest. In the current work, application of guided waves is investigated in ice detection on composite materials which is a well-known problem in wind turbine industry.

The possibility of detecting a layer of ice on a composite plate is first investigated by a 2D isotropic-anisotropic multilayer model. The wave equation is solved and dispersion curves are obtained. Results show that adding a second isotropic layer on top of an anisotropic material causes reduction in phase and group velocity of the first symmetric mode.

Effects of low temperature on the received signal is investigated using an experimental test setup. Measurements show that lowering the temperature causes drop in amplitude and temporal phase shift in the received signal. These effects were handled by a modification of the Baseline Signal Stretch method. The modification is based on decomposing the signal into symmetric and asymmetric modes and applying two different stretch factors on each of them.

Computational modelling of the problem is performed by first developing a 2D model which shows that accretion of ice causes reduction in phase and group velocities of the incident wave and creates reflections. The model is developed further to a 3D shell model, in which ice is placed on the plate by changing the properties of specific elements in the icing region. The Baseline Signal Stretch with the mode decomposition method is applied to the model for temperature variations. Effects of ice accretion on a composite plate is studied in time, frequency and wavenumber domains. In each case post-processing approaches are introduced for this specific application. Moreover, icing index is introduced which is sensitive to accumulated ice on the plate.

The experimental study is performed in a cold climate lab in three different steps. The first part to get general understanding about the effects of ice accretion on waves propagating in a composite plate. Next, to understand the effects of temperature on the received signal and calibrate the temperature model and finally a more accurate study by installing 24 accelerometers and manufacturing a layer of ice on the plate to validate the results obtained by the computational model.

Using the model and introduced criteria both thickness and location of ice on the plate are identified. All the results show that application of guided waves is a promising and accurate tool in ice detection on composite plates.

Keywords: Guided waves, composite, ice detection, wind turbine, low temperature

Preface

The current work is part of the project ”Ice detection for smart de-icing of wind turbines” and it has been carried out between December 2013 and September 2016 at the Department of Applied Mechanics at Chalmers University of Technology. It is funded by the Swedish Energy Agency, which is gratefully acknowledged.

First I would like to thank my supervisors Professor Viktor Berbyuk and Professor Anders Boström for guiding and supporting me since the beginning of the project until now. I am also greatfull for all the support I recieved during the experimental work from Mr. Jan Möller.

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Finally, I would like to thank my family. I love you. I wouldn’t be here without your help and support.

Gothenburg, September 2016
Siavash Shoja

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A S. Shoja, V. Berbyuk, and A. Boström. ”Investigating the application of guided wave propagation for ice detection on composite materials”. *Proceedings of International Conference on Engineering Vibration, Ljubljana.* 2015, pp. 152-161

Paper B S. Shoja, V. Berbyuk, and A. Boström. ”Effects of temperature variations on guided waves propagating in composite structures”. *Proceedings of SPIE.* vol. 9806. 2016, p. 980605-980605-11

Paper C S. Shoja, V. Berbyuk, and A. Boström. ”Application of guided waves for ice detection on composite structures”. *To be submitted for international publication*

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work, *i.e.* planning, developing theory, analytical and numerical modelling, performing simulations, experimental work, post-processing and writing of the papers, all with the assistance of the co-authors. Several results of the project work have been also presented at the following conferences:

- Shoja, S., Berbyuk, V., and A. Boström, (2015): Ultrasonic guided waves approach for ice detection on wind turbines, In Winterwind International Wind Energy Conference 2015, Piteå, Book of Abstract, page 17.
- Shoja, S., Berbyuk, V., and A. Boström, (2015): Towards application of ultrasonic guided waves in ice detection on wind turbines, In International Conference on Advances in Vibrations, Porto, Portugal, March 30-April 1, 2015, Book of Abstract, page 18.
- Shoja, S., Berbyuk, V., and A. Boström, (2016): An approach in using guided waves for ice detection on wind turbines, In Winterwind International Wind Energy Conference 2016, Åre, Book of Abstract, page 61.

Contents

Part I
Extended Summary

1 Introduction

Guided waves are an efficient tool in fields of inspection, detection and non-destructive evaluation when it comes to elongated structures. Even though they are used recently in many fields, the background of studying them goes back than a century. The main application of guided waves is in structural health monitoring (SHM) and non-destructive testing (NDT). In this project it is tried to study the possibility of using guided waves for ice detection which is one of the well-known problems in wind turbine industry. In this chapter first a brief review of guided waves is given, then icing problem in wind turbines and methods of detections are explained. Finally the aims and objectives of the project are given.

1.1 A brief review of guided waves

The history of elastic waves in solids is linked with the research that has been done in nineteenth century. One of the original works which is the reference of many current studies was presented by Lord Rayleigh [1]. In his work, propagation of elastic waves was studied along the surface of a semi-inifinite solid, now known as Rayleigh waves. By adding one more surface to the semi-infinite solid and solving for the simplest possible solution, Love [2] was able to identify one more wave in the horizontal direction. These waves are known as Love or Shear Horizontal (SH) waves. Lamb [3] limited the solid in the other direction and studied the propagation of waves in layers which are known as Lamb waves. He managed to find the exact solution for both of the modes which are generated in the solid and known as symmetric and antisymmetric modes. The main focus of Lamb was on isotropic materials.

By introducing new types of materials into industry there was a need of studying the propagation of Lamb waves in anisotropic and layered anisotropic materials. A comparison between propagation in isotropic and anisotropic media shows that the wave propagation problem is notoriously complicated when it comes to anisotropic media. This is mainly because in the isotropic case the wave is dispersed into two modes of longitudinal and shear waves (shear vertical and shear horizontal). In anisotropic media, however, pure longitudinal and transverse waves are not produced anymore and the wave is dispersed into three wave packets of which one is quasi-longitudinal and two are quasi-shear waves. Considering the complexity of the problem, uncoupling the wave into longitudinal and shear waves is not possible with simple algebraic methods. In the anisotropic case, there are three surfaces, one for quasi-longitudinal and two for quasi-shear waves and the incident and reflected waves can not be thought as purely longitudinal or shear. Here the waves can be uncoupled by solving a sixth order polynomial equation [4].

Composite materials, however, can not only be treated like anisotropic materials due to their inhomogeneities. In order to solve the propagation of Lamb waves analytically in composite materials two methods can be used:

1. Solve the wave equation for the multilayered anisotorpic structure.

2. Homogenize the composite plate and solve for one single layer of anisotropic material.

Many methods are introduced in order to solve the wave propagation problem in multilayared media. One of the early works was proposed by Thomson [5] who introduced the transfer matrix method. In this method the formal solution is obtained in one layer and it is extended to top and bottom surface of the neighbour layers by applying continuity conditions (equal stress and displacement). Another method was introduced later by Knopoff [6] known as the global matrix method which consists of all of the equations for all of the layers.

Homogenizing the composite material into a single anisotropic layer with equivalent characteristics, however, makes the wave propagation problem easier to solve. Homogenization can be used both in analytical and numerical solutions of the wave propagation problem. Classical laminate theory is a well-known method of homogenization in composite materials.

Using any of the mentioned methods, it is possible to obtain the relationship between frequency, phase and group velocities, mode and thickness which is known as the dispersion relation. By solving the dispersion relation, dispersion curves are obtained which provide general information about the medium when waves propagate inside it.

The name of guided wave (GW) is used when it comes to application of Lamb waves in non-destructive evaluation which basically refers to propagation of Lamb waves in finite media. Since the GWs are guided by the boundaries of finite media, they are able to propagate along long distances. This makes them a suitable choice when it comes to NDT and SHM in elongated structures. Much research has been done for damage detection and identification. One of the earliest studies in this topic is done by Worlton [7]. In his work, he studied and compared the dispersion curves of two aluminium and zirconium plates and introduced it as a potential NDT method. Over the decades, much research has been done in fault detection using GW and new methods have been introduced. The procedure of a proper fault detection method is divided into different sub-levels [8]:

- Detection: Give binary information about the existence of damage in the structure.
- Localization: Quantitative information about the location of damage.
- Assessment: Information about the severity of damage.
- Prediction: Data regarding the safety of the structure.

Although many of the methods are introduced for detection of damages in the media but they are mostly based to detect any changes on them. Therefore, it is possible to use the GWs not only to detect damages on the structures but also for other applications like detection of ice accumulating on them.

1.2 Icing problem on wind turbines

Some of the best places to install wind turbines are located in cold regions. Turbines operating in these regions have higher potential of wind power due to higher density of air and wind speed [9]. At the same time, wind turbines operating there face icing conditions. Due to cold temperature ice start to accumulate on wind turbine blades which

(a) (b)

Figure 1.1: *(a)Warning board for ice throwing (b)Wind turbine facing icing condition.*

creates various problems like reshaping the air-foil of blades, increasing drag, mechanical failure due to higher loads on the blades, undesired vibrations, etc [9–11]. Beside all the direct problems, ice throwing is a problem that prevents turbines to be installed close to residential areas or roads [12]. All of these problems cause the performance of wind turbines to drop up to 30% [13]. Many of wind turbines are facilitated with a de-icing system, however, in order to optimize it, an accurate ice detection method is needed.

The current methods of detection are reviewed by Parent *et al.* [9] and Homola *et al.* [11]. Methods of detection are either based on condition monitoring, like measuring temperature and dew point, comparison between the expected and current power generation, frequency of generated noise, change on blade resonant frequency or direct methods like using ultrasonic waves, thermal infrared technique, electromagnetic waves, optical methods and guided waves [9, 11, 14–25].

Use of guided waves for detection of ice is proposed as one of the potential and accurate methods due to all its special characteristics. The application was investigated before by several authors which were mostly based on detection of ice on an isotropic material for aircraft applications [14, 22, 26].

Detection of ice on wind turbines, however, makes a different problem than in metals due to the blade's anisotropicity and high attenuation ratio. A patch of ice which is interesting to detect can be larger than is looked for in the aircraft industry. Moreover, due to the large size of wind turbine blades which in some cases can be up to 80 m long and high damping characteristics, the frequency of excitation should be lower than in classical NDE methods. The method which is investigated should be able to give as much information as possible about the accumulated ice. This can be thickness, location, length and preferably type of ice. Knowing these parameters helps the manufacturers to optimise their de-icing systems.

A conceptual design of an accurate ice detection system is according to figure 1.2. The system is a combination of three physical, virtual and decision making units. A database can be obtained in the virtual unit using a computational model. In this part data about the characteristics of the turbine blade should be given as input data. Hardware of the system is located in the physical unit which includes the accelerometers, transducers and data acquisition systems. Information from the both virtual and physical units are collected in the decision making unit (DMU). The unit is able to make automatic decisions however help of an operator can be used in this part. The decision made in the DMU has detail information about thickness, length, location and type of ice which is sent to the de-icing system.

In the current work application of guided wave propagation for ice detection on wind turbine blades is investigated. A composite plate is used as the structure for simplicity.

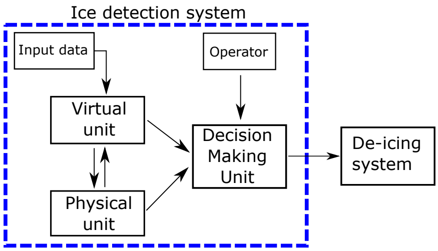

Figure 1.2: *The conceptual sketch of an ice detection system.*

1.3 Aims and objectives

The main aim of the project is to study propagation of guided waves in composites by analytical and computational methods. Using classical computational methods make the problem expensive to solve and here the aim is to develop simple methods and implement them into the computational model for simplification. Effects of conditions like temperature on the propagating wave is significant, therefore, developing simple methods and applying them into the model is important.

Developing and implementing methods of signal processing for this specific application is the other goal of the project. Many of the introduced methods are related to fault detection using GWs and in order to extent the application of GWs new methods should be introduced.

Finally, many objectives are observed including creation of the test set-up, ability of specific hardware to work at low temperatures and filtering the noise. Designing the test set-up and tools for specific reasons like ice manufacturing are done cost efficient and simple and expensive ways like using wind tunnels are skipped in this project.

2 Methods of study

Methods of studying the application of guided waves for ice detection are given in several steps. The first step is to get a general idea about the possibility of detecting ice on a composite layer. This step is done by solving and comparing the dispersion curves. Next a computational model is developed to simulate the propagation of guided waves in a composite plate. The model is computationally efficient and it is developed by applying simplifications in several steps. Model validation and part of the study are performed using a physical prototype in a cold climate lab. Finally, the results and measurements are investigated by introducing several criteria using signal processing methods.

2.1 Dispersion curves

As explained previously solving the dispersion relations leads to dispersion curves which give general information about propagation of guided waves in media. The dispersion curves are the relationship between the frequency and phase or group velocity for different wave modes.

The effects of ice accretion on guided waves propagating on a plate can be gained by comparing the dispersion curves for two cases of one layer and two layers which the second layer representing the ice layer. This has been done before by Rose [26] for an isotropic plate and it is done in this study for an anisotropic plate and a second layer as ice layer on the top (Paper A).

2.2 Computational model

Some analytical methods of solving wave equations are previously mentioned. The methods have limitations of not being extendible to more complicated geometries. Therefore, a computational model is needed in order to be able to solve the wave propagation problem for different icing scenarios. Some of the early works of numerical modelling of propagation and scattering of stress waves were done by Bond *et al.* [27], Blake *et al.* [28] and Temple [29] during the 1980s. They used finite difference and finite element methods to numerically solve the wave propagation problem.

The main challenge of solving a wave propagation problem using finite element method, is considering the right temporal and spatial resolution in a way that convergence would be reached. Previous literature proposed the temporal resolution to be 20 points per cycle of the highest frequency and the spatial resolution to be 10 to 20 nodes per smallest wavelength [30–32]. This makes the computational model expensive to solve.

In the current work, the complexity of the model is reduced in several steps by simplifications and assumptions. The composite plate is homogenized and modelled as a single layer orthotropic plate with equivalent characteristics. This assumption would make inaccuracy for large frequency-thickness ($f \cdot d$) values, however, for low frequencies give reasonable results [33]. Moreover, the plate is modelled using shell elements with 6 degrees of freedom on each node. Shell elements are also limited to low $f \cdot d$ values and higher order modes are not fully resolved due to the assumptions made regarding the displacement field in the thickness direction [34]. However, accurate results are reached in the range of $f \cdot d$ used in this study.

The next challenge in computational modelling is to apply the effects of temperature into the model. Previous studies have shown that change of temperature is one of the main sources of fluctuations in the received signal [35–38]. Fluctuations are due to effect of temperature on the test object, piezoelectric materials, cables and the bonds. Temperature

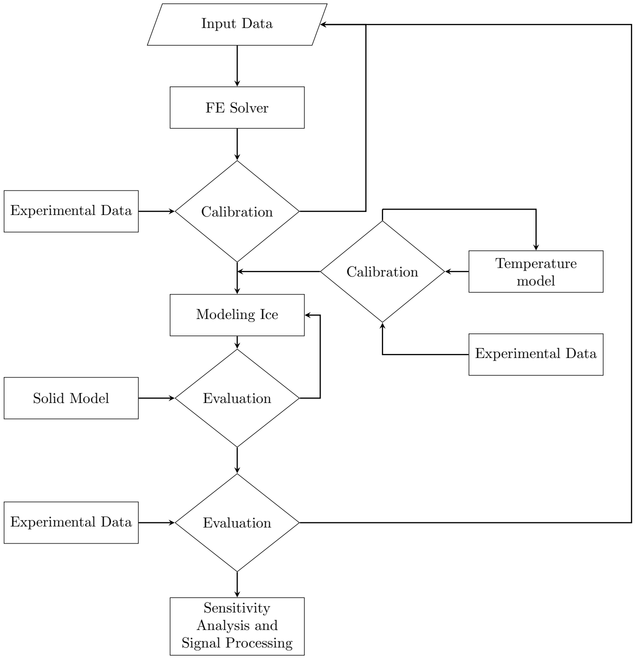

Figure 2.1: *Flowchart of the computational model.*

can be included into the FE model [39] which changes the FE model from a mechanical model to a coupled thermal-mechanical one. This makes the FE model more complicated and expensive to solve. Effects of temperature can also be applied directly on the received signal. Some models have been proposed based on stretching and changing the amplitude of signal with relation to temperature [40]. The model which is used in this work is a signal stretch method based on mode decomposition which separates the wave modes in the received signal and applies two different stretch factors to them taking into account the changes in temperature (Paper B) [41].

Modelling the ice layer on the work object can also be done with modelling a new geometry and mesh with shell elements. However, more elements will be needed and contact boundary conditions between the layers would be added into the FE model. In this study the ice layer is modelled by homogenizing the characteristics of ice with the plate in elements in the icing region. Performing this, the complexity of the model reduces more without loosing significant accuracy. The FE model is calibrated and validated in several steps using the experimental measurements and a FE solid model (Paper C). Figure 2.1 shows the flowchart of different steps in the FE model.

2.3 Experimental work

The experimental study is done in a cold climate lab with the ability to change the temperature down to $-25°C$. The lab contains a freezer and a control room (Fig. 2.2). The data acquisition (DAQ) system is made by National Instruments (NI) and Labview is used as the main controlling software. In order to confirm the input and output signals, two oscilloscopes are connected to the system prior to NI DAQ. An amplifier is connected to the generated signal for magnification of the voltage.

(a) (b)

Figure 2.2: *(a)Test object under icing conditions (b)Control room.*

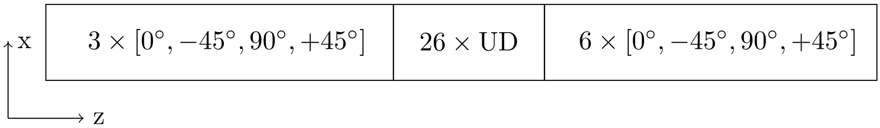

Figure 2.3: *Schematic view of the layups of the composite plate.*

The used plate is a rectangular glass-fibre composite plate with 62 plies and Vinylester resin and it is a type of material which is common to use in the wind turbine industry. Figure 2.3 shows the schematic view of the layups. The dimensions of the plate are $0.02 \times 0.2 \times 8$ m and it is excited by means of a magnetostrictive actuator using Terfenol-D. Details about the design of the transducer is fully described in previous work [42]. The excitation signal is a tone-burst signal with the centre frequency ranging from 3 kHz to 7 kHz. Higher excitation frequencies are not supported by the transducer.

To measure the acceleration of the displacements of the propagating wave, piezoelectric accelerometers of the type IMI608A11 are used with coaxial cables RG58. Accelerometers are mounted inside aluminum cubes and glued on the surface of the plate. Mounting is done in such a way that they mostly measure the signal in the longitudinal direction. The output of the accelerometers is an electric signal that is sent to an NI DAQ for post-processing.

Three different experiments are done using the test setup:

- Experiment using 2 accelerometers to get an overall view about the effect of temperature and ice accretion on the plate.

- Experiment using 24 accelerometers equally distributed on the plate to accurately measure the signal by changing temperature.

- Experiment using 24 accelerometers equally distributed on the plate to measure effects of ice accretion on received signal accurately.

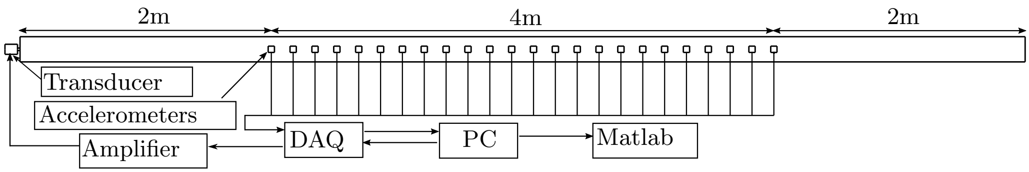

Figure 2.4: *Schematic view of the test setup.*

Since the frequency of noise is close to the excitation frequency, one of the main challenges in the experimental study is to filter the received signal. In order to reduce the noise, each experiment is done 9 times and their mean value is used as the final measurement data. Doing this, it is possible to reduce the noise amplitude by 30%. A Gaussian filter is then applied on the measured data.

Production of ice is performed by spraying water on the surface under low temperature. In order to manufacture rime ice, the temperature should be lower than for glaze ice so the droplets freeze the air. Moreover, the distance from the spraying device to the surface of the test object is important. Larger distance helps the droplets to have more time to be frozen before hitting the surface and create rime ice. On the other hand the droplets remain liquid while hitting the surface for lower distances from the test object and they freeze on the surface which makes glaze ice. Since in this study ice manufacturing is performed manually, the manufactured ice is a mixture of glaze and rime ice. A wind tunnel can be used in future in order to control the process and manufacture two types of ice separately.

The set-up used in the cold climate lab can be used as a physical prototype of ice detection system and it can be applied on a wind turbine blade in future for further studies.

2.4 Signal processing

Data obtained from both experiment and simulation should be transformed and processed to get different type of information. The transferring and processing can be done using mathematical, statistical, computational and heuristic formulations and techniques. The methods can either be based on a baseline signal or baseline-free. In case a baseline signal is needed, the changes in the structure are detected by comparing the baseline signal and the current signal. This study is based on comparing signals for a period of time, therefore, the presented results are based on a baseline signal.

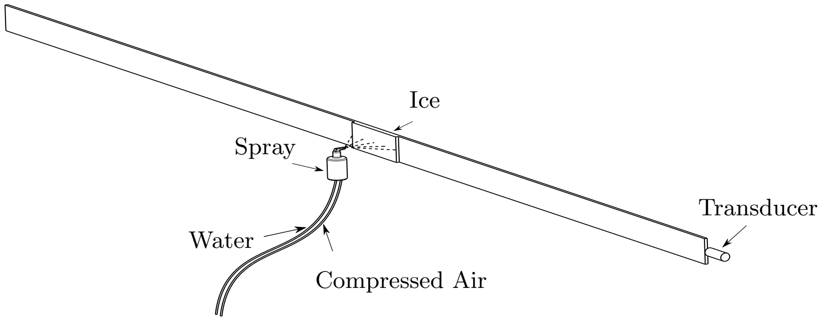

Figure 2.5: *Schematic view of ice manufacturing setup.*

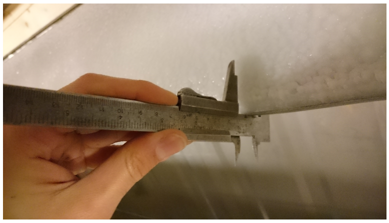

Figure 2.6: *Manufactured mixed ice on the plate.*

The processing methods in GW propagation are usually done in time, frequency or wavenumber domains. Methods of processing the signal in the time domain are based on change in amplitude of the received signal, mode conversion due to reflections, Time-of-Flight (ToF) and phase shift [43, 44]. In the frequency domain Fourier transform of signal is used to analyse the wave response [45]. In order to make the Fourier transform a function of time, short-time Fourier transform is defined [46]. The procedure of processing the signal can also be done in wavenumber domain which gives information about dispersion of waves and changes of velocities of different wave modes with respect to frequency [31, 47].

Based on any domain, indices are defined which give binary information about any changes in the structure. The indices can be based on amplitude or ToF [48, 49], signal energy [50–52], attenuation [53] or statistical methods [54].

Many of the signal processing methods are introduced for damage detection in the structures. These methods can be used in the current study, however, due to different physics of the problem they should be modified. Investigating the effect of ice accretion in different domains help to introduce new indices to detect ice on a laminate.

The results obtained using the computational model and experimental work are investigated in time, frequency and wavenumber domains and the changes due to icing conditions are observed. An icing index is defined to get binary information about existence of ice and should be further studied (Paper C).

3 Summary of appended papers

3.1 Paper A

Application of guided wave propagation for ice detection is studied by first determining the dispersion curves and comparing between one layer anisotropic and two layers of isotropic-anisotropic materials. The drop in phase and group velocity of symmetric mode is observed. The study is continued using a 2D FE model and reflections and temporal phase shift after icing conditions is detected due to adding a layer of ice on top of the first layer. Measurement is done in the cold climate lab and it is shown that lowering temperature has significant effects on the received signal. Moreover, due to icing conditions, reflections and change in group velocity of symmetric mode is also observed which follows the results obtained using the FE model.

3.2 Paper B

Effects of temperature variations on GWs propagating in a composite plate in investigated further in the cold climate lab. The range of temperature examined in this study is between 25° C to -25° C and effects of temperature variations on amplitude and phase shift of the received signal are investigated. It is observed that Baseline Signal Stretch (BSS) method is not an appropriate approach to handle the effects of temperature on the received signal on composite materials due to their orthotropic charactristics. Therefore, it is modified and apply with two different stretch factors for Symmetric and Asymmetric wave modes. Experimental results show that an improvement is obtained using the BSS with the mode decomposition method at temperature variations of more than 50° C.

3.3 Paper C

Application of guided waves for ice detection on composite structures is further studied by introducing a computational model. The model is simplified in several steps to make it computationally efficient and went successfully through validation using experimental data. Effects of ice accretion on propagation of guided waves are studied in time, frequency and wavenumber domains. New approaches are introduced in each domain for better understanding the changes. Moreover, an icing index is also introduced for ice detection giving binary output about existence of ice on the composite plate. All the methods are examined on experimental measurement when ice is manufactured on the plate. Results show application of guided waves is a promising method for early ice detection and can be used in wind turbine industry.

4 Concluding remarks and outlook

GW propagation in composite materials is studied using a computational model. Several simplifications are applied to the model in order to make it cost efficient. Methods of signal processing are developed and implemented for application of ice detection on wind turbine blades.

Icing problem is currently one of the main barrier of wind turbines operating in cold climate regions. In order to overcome this problem both an accurate ice detection system and optimized de-icing system are needed. In this project application of GW propagation is studied for ice detection for wind turbine industry.

The primary work which is an analytical model and solving for dispersion curves show that the changes in phase (or group) velocity can be reached by adding a second layer on top of the main composite layer. This proves that GWs have the potential to be used for ice detection.

It is observed that the effect of temperature variation on the composite and piezoelectric materials is significant and it should be taken into account in the computational model. An approach is proposed to handle these effects and it is applied later into the computational model.

The computational model is developed first as a 2D model to get an overview about the expected results. The model is then developed to a 3D shell model.

Experimental work is done on a composite plate in a cold climate lab to study the effect of ice accretion on GWs, effects of low temperature on GWs and validate the computational model.

Several criteria are used to analyse and understand the received signal both from the simulation and experiment. The criteria are in time, frequency and wavenumber domains. An icing index is also introduced to get a binary response about the existence of ice on the plate using only one sensor on the plate.

Moreover, experimental work is performed in a cold climate lab for calibration and validation of results obtained in previous steps. The calibration is performed on the introduced thermal model. The criteria and icing index are applied to the experimental data after manufacturing ice on the plate and good agreement has been observed compared to computational results.

All results show GWs are a promising tool for accurate ice detection on composite structures and should be investigated further.

4.1 Outlook

The current study, the developed model and experimental set-up, can be used and be the base of other topics in future. In this part it is tried to mention some of the potential topics for further study.

Developing the model. Although the current computational model is validated and the obtained results are reasonably accurate, it can be developed further. Previously it is shown that attenuation due to characteristics of materials influences the received signal. Applying damping to the model can lead to more accurate results.

The methods of signal processing can also be studied further using the computational model.

Ice type. As described previously, different type of ice can be accumulated on the blade. Therefore, knowing the special characteristics of ice like density and Young's modulus can help to optimize the energy needed for de-icing. The current method can be used for further study to detect the type of accumulated ice.

Wind turbine blade model. For further studies of application of GWs in wind turbine industry, the computational model can be applied to a blade geometry. Moreover, effects of location of the sensors on the results can be investigated. Optimizing the location of the sensors to get the best possible resolution can also be done in future.

Further experimental work. The experimental studies can be applied on a wind turbine blade. A wind tunnel can be used for accurate ice manufacturing and the detection system can be applied in situ.

De-icing. Ultrasonic guided waves can be used to de-ice the wind turbine blades. By choosing an optimum wave mode and frequency, ultrasonic guided waves can induce delaminating transverse shear stress at the interface between the ice layer and the substrate structure [55–58]. The current computational model and physical prototype can be developed more to study de-icing on wind turbine blades using GWs.

SHM and NDE of wind turbine blades. Testing, inspection and monitoring the wind turbine blades are an important factor for keeping them in continued operation. A life-span of 20 years is expected in wind turbine industries and high cost of the blades rises the motivation of accurate inspection of them. GWs are previously proposed and used in terms of SHM in the wind turbine industry [59]. The developed computational model in the current work can be expanded further and be used to study and develop new methods of SHM and NDE for wind turbine blade.

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