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Guided wave-based approach for health monitoring of composite structures

Application to wind turbine blades

SIAVASH SHOJA

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2018

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOLID AND STRUCTURAL MECHANICS

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ISBN 978-91-7597-821-5

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr. 4502
ISSN 0346-718X
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Chalmers Reproservice
Göteborg, Sweden 2018

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Abstract

The use of composite materials has increased in manufacturing of large structures. These structures can be subjected to different types of defects, for which detection has always been a challenge. Wind turbine blades are a perfect example of these large structures that can be exposed to different defects such as delamination, debonding or ice accumulation during the turbine operation. Tools based on guided waves can be used for health monitoring of such structures. The special characteristics of guided wave-based tools such as mobility, rapidity and cost efficiency make them interesting to be used for non-destructive testing and structural health monitoring. Besides these general characteristics, what makes the guided waves a good choice for health monitoring of large structures is that they have the ability to propagate long distances. The size of these structures and their high damping require the use of low frequency guided waves, which are in focus of the present project. The ultimate goal of this work is to investigate the application of guided waves for health monitoring of large composite structures with focus on wind turbine blades. The investigation has been carried out using calculations of dispersion relations and numerical simulations of guided wave propagation in composite materials. In order to make the numerical model computationally efficient, the possibility of using material homogenization methods has been investigated for guided waves propagating in the low range of frequencies. The homogenization methods are aimed at being used for both composite laminates and delamination regions. A similar study is performed on sandwich structures since they are used as parts of large structures. In order to overcome the effects of high attenuation properties of the structures a design optimization method is developed and proposed to create special arrays of transducers for generation of guided waves. The main aim of the designed arrays is to evenly distribute the wave energy in the area of interest in a domain. The developed methods and conclusions have been used to study the propagation of guided waves in wind turbine blades with focus on detection of defects and accumulated ice. The research has been supported by experimental studies for different part of the project. Results show that the developed numerical methods can be used to simulate guided wave propagation in composite laminates. Moreover, the specifically designed arrays of transducers are able to evenly distribute the wave energy in large structures. Finally, it is observed that guided waves can be used to develop multifunctional smart systems for defect and ice detection on wind turbine blades.

Keywords: Guided wave propagation, structural health monitoring, composite structures, wind turbine blades, ice detection, numerical simulations, design optimization

Preface

The current work has been accomplished during December 2013 until November 2018 at the department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden. It was funded by the Swedish Energy Agency within the project "Ice detection for smart de-icing of wind turbines" which is gratefully acknowledged.

First of all, I would like to thank my supervisors Prefessor Viktor Berbyuk and Professor Anders Boström for all their support during these years. Mr. Jan Möller is gratefully acknowledged for the help during the experimental work.

Next, I would like to thank my colleague and co-author, Dr. Samir Mustapha from the American University of Beirut for the interesting joint work.

I would also like to express my gratitude to members of the research group, Lightweight Materials and Structures of Chalmers University of Technology for the valuable comments and discussions at the meetings.

Further, I would like to thank all my friends and colleagues at the Divisions of Dynamics and Material and Computational Mechanics for the nice working environment. It was a pleasure to work with all of you. Particularly, I would like to acknowledge my friend Dennis Wilhelmsson for all the great discussions that made the working time more enjoyable.

Last, but definitely not least, I would like to thank my family for their love, support and encouragement that helped me during these years.

Gothenburg, October 2018
Siavash Shoja

Thesis

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

Paper A Shoja, S., Berbyuk, V., and Boström, A.,"Delamination detection in composite laminates using low frequency guided waves: Numerical simulations", *Composite Structures*, 2018, **203**(1): pp. 826-834, ISSN: 0263-8223, doi: 10.1016/j.compstruct.2018.07.025.

Paper B Shoja, S., Berbyuk, V., and Boström, A.,"Guided wave energy transfer in composite sandwich structures and application to defect detection", *Accepted for Publications in the Journal of Shock and Vibration*, 2018.

Paper C Shoja, S., Berbyuk, V., Mustapha, S.,"Design optimization of transducer arrays for uniform distribution of guided wave energy in arbitrarily shaped domains", *Submitted for publication in the Journal of Intelligent Material Systems and Structures.*

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

Paper E Shoja, S., Berbyuk, V., and Boström, A.,"Guided wave-based approach for ice detection on wind turbine blades", *Wind Engineering*, 2016, **42**(5): pp. 483-495, doi: 10.1177/0309524X18754767

Paper F Shoja, S.,"A guided wave-based transducer array system for structural health monitoring of a wind turbine blade", *To be submitted for international publications.*

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 A-F, all with the assistance of the co-authors. The experimental validation of paper C is performed by Samir Mustapha.

In addition to papers A-F, the following conference publications have also been part of the research in this PhD project which are not included in this thesis:

1. Shoja, S., Berbyuk, V. and Boström, A. "Ultrasonic guided waves approach for ice detection on wind turbines", in *Winterwind, International Wind Engineering Conference.* 2015, Piteå, Book of Abstract, page 17.

2. Shoja, S., Berbyuk, V. and Boström, A. "Towards application of ultrasonic guided waves to ice detection on wind turbines", in *International Conference on Advances in Vibrations.* 2015, Porto, Book of Abstract, page 18.

3. Shoja, S., Berbyuk, V. and Boström, A. "An approach in using guided waves for ice detection on wind turbines", in *Winterwind, International Wind Engineering Conference.* 2016, Åre, Book of Abstract, page 61.

4. Shoja, S., Berbyuk, V. and Boström, A. "Effects of temperature variations on guided waves propagating in composite structures", in *Proceedings of SPIE - The International Society for Optical Engineering. Vol. SPIE 9806.* 2016, Las Vegas, pp. 980605-1-980605-12.

5. Shoja, S., Berbyuk, V. and Boström, A. "Computational modelling of guided wave propagation for ice detection on composite materials", in *29th Nordic Seminar on Computational Mechanics, NSCM-29, R. Larsson (Ed.).* 2016, Gothenburg, pp. 1-4.

6. Shoja, S., Berbyuk, V. and Boström, A. "Effects of delamination on guided wave propagation in laminated composite beams – Numerical simulations", in *Svenska mekanikdagar* 2017, Uppsala, pp. 1.

7. Shoja, S., Berbyuk, V. and Boström, A. "Modelling of guided wave propagation for detecting delamination in large composite structures", in *Proceedings of the 12th European conference of non-destructive testing* 2018, Gothenburg, pp. 1-3.

8. Shoja, S., Berbyuk, V. and Boström, A. "Application of low frequency guided waves to delamination detection in large composite structures: A numerical study", in *Proceedings of the 18th European Conference on Composite Materials* 2018, Athens, pp. 1-7.

Contents

Part I
Extended Summary

1 Introduction

Decades of using fossil fuels for energy production caused today's "global warming" situation. At the same time, the rise in the population of the world increases the energy demand. Until the day that a global solution is found for the energy problem, we do not have a choice but using a combination of available green and renewable energy resources. Among these resources, wind power can play a key role in providing the energy of the future. Currently, an obstacle that prevents increasing the use of wind turbines is their higher cost to energy output ratio compared to fossil fuels. One way to tackle this problem is to increase the life span of the turbines by preventing catastrophic failures. A review of failure cases of wind turbines show that blade failure by 23% is ranked first, see Fig. 1.1 [1]. This shows that preventing blade failure can lead to a significant cost reduction on manufacturing and maintenance of wind turbines.

A comprehensive study is performed by Sørensen et al. [2] which shows that there are seven major types of damage on the blades, see Fig. 1.2. Any of these types of damage might lead to total failure of the blade. Along the same line, the maintenance cost can be reduced when damage is discovered at an early stage. This requires early damage detection that can be done by constant structural health monitoring (SHM) of the blades.

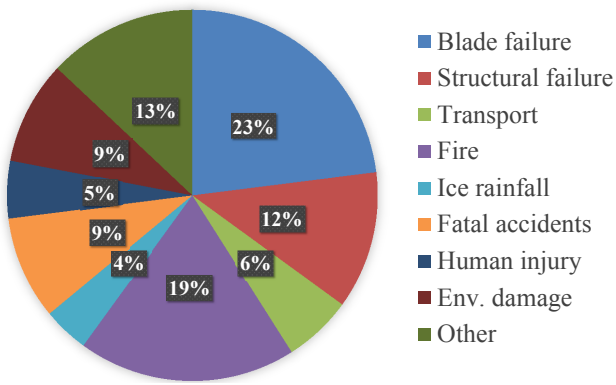


Figure 1.1: *Failure types of wind turbine accidents [1].*

A multifunctional SHM of wind turbine blades can not only be used for damage detection, but also for icing problems. This problem occurs for wind turbines operating in cold regions, see Fig. 1.3. Due to cold temperature ice starts to accumulate on wind turbine blades which creates various matters like reshaping the air-foil of the blades, increasing drag, mechanical failure due to higher loads on the blades, undesired vibrations, etc [3–5]. Besides all the mentioned issues, ice throwing is a threat that prevents turbines to be installed close to residential areas or roads [6]. All of these problems cause the performance of wind turbines to drop up to 30% [7]. Many wind turbines are facilitated with a de-icing system, however, in order to optimize it, an accurate ice detection method is needed.

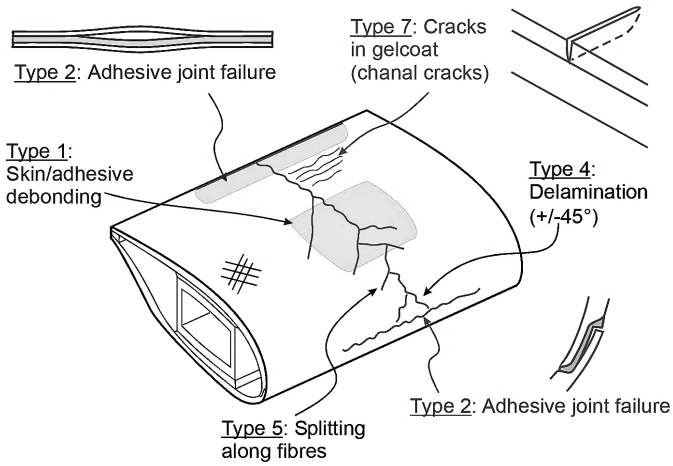


Figure 1.2: *Different types of blade damage [2].*

Several authors have reviewed the available methods of ice detection on wind turbine blades [3, 5]. Methods of detection are either based on condition monitoring, like measuring temperature, 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 (GWs) [3, 5, 8–18].

Use of GWs for detection of ice is proposed as one of the potential and accurate methods due to their special characteristics. Ice detection using the GWs has been investigated previously by several authors which are for isotropic materials for aircraft applications [8, 15, 19, 20].

Furthermore, reviews on methods of SHM of wind turbine blades show that the majority of the methods are vibration-based such as ultrasonic techniques, acoustic emission (AE) and GWs [21–27]. Among these methods, the GW techniques have a higher potential to be applied on a full-scale blade and are capable of detecting location and severity of the defects [28].

Investigating the possible application of GWs as a SHM tool for wind turbine blades has been the ultimate goal of the current project. The goal has been carried out in two parts:

- Investigating the application of GWs to ice detection on composite materials with the aim of applying the technique on wind turbine blades.

- Possibility of developing the application further to a defect detection system on wind turbine blades.

These investigations require full understanding of the theory of GW propagation in composite materials and their interaction with the common types of defects.

Figure 1.3: *A wind turbine with ice accumulation condition.*

The special characteristics of composite materials have lead to a rapid growth of their usage in different industries. Together with this rapid growth the need of developing methods of SHM and non-destructing testing (NDT) for such materials is becoming more transparent. The main challenges of using GWs for defect detection in composite materials are: understanding the effects of anisotropy, overcoming the high attenuation characteristics and adapting them to special types of defects in special applications. These challenges lead to the general issues of the PhD project:

- To understand the behaviour of GWs in composite materials by dispersion calculations.
- To efficiently simulate the propagation of low frequency GWs in composite materials.
- To introduce methods for overcoming the effect of high attenuation in composite materials.
- To experimentally study and verify the developed approaches and the used techniques.
- To develop signal processing techniques proper to such applications.

These are the main research questions that have arisen during the project and are briefly explained in the next sections. These research questions resulted in several publications appended in part II. The focus of the publications are on GW propagation in composite materials and sandwich structures in **papers A** and **B** and on developing a method to overcome the effect of high attenuation in **paper C**. Furthermore, application of GWs for SHM of wind turbine blades has been specifically studied for better understanding. The studies are focused on ice detection in **papers D** and **E**, together with defect detection in **paper F**.

2 Guided waves in composite materials

The history of elastic waves in solids starts with the research that was done in the nineteenth century. One of the earliest papers, which is the reference of many current studies, was presented by Lord Rayleigh [29]. In his work, propagation of elastic waves was studied along the surface of a semi-infinite solid, now known as Rayleigh waves. By adding one more surface to the semi-infinite solid and solving for the simplest possible solution, Love [30] was able to identify one more surface wave polarized in the horizontal direction. These waves are known as Love waves. Lamb [31] limited the solid in the other direction and studied the propagation of waves in plates which are known as Lamb waves. He managed to find the exact dispersion relation for both types of modes which are generated in the solid and known as symmetric and antisymmetric modes.

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 divided into 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 divided into three wave types 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 as simple as in isotropic materials. The waves can be uncoupled by solving a sixth order polynomial equation [32]. This equation is known as the "dispersion relation" and by solving it, general behaviour of wave propagation in the media can be explained by the curves in the frequency-wavenumber domain known as the "dispersion curves".

2.1 Dispersion curves

Calculation of dispersion curves in an anisotropic material can be done by solving the equation of motion representing the characteristics of the material in three directions. However, due to layup inhomogeneities of composite laminates they cannot be calculated in a similar manner and the layups should be connected together.

Many methods are introduced in order to solve the wave propagation problem in multilayared media. One of the early studies was performed by Thomson [33] who introduced the transfer matrix method. In this method, a transfer matrix is developed for a number of layers by extending the solution from one layer to the next one while satisfying the interfacial continuity conditions (equal stress and displacement). Another method was introduced later by Knopoff [34], known as the global matrix method, which uses all of the equations for all of the layers simultaneously. Using these equations, the dispersion curves are calculated in **paper D** for a case of two layers of materials.

The global matrix method accurately calculates dispersion curves in multilayer materials, but by increasing the number of layers the size of the matrix increases and the problem becomes more complex. Calculation of the dispersion curves of such materials can be done using the Floquet-Bloch (FB) theory [35]. Assuming that the general solution

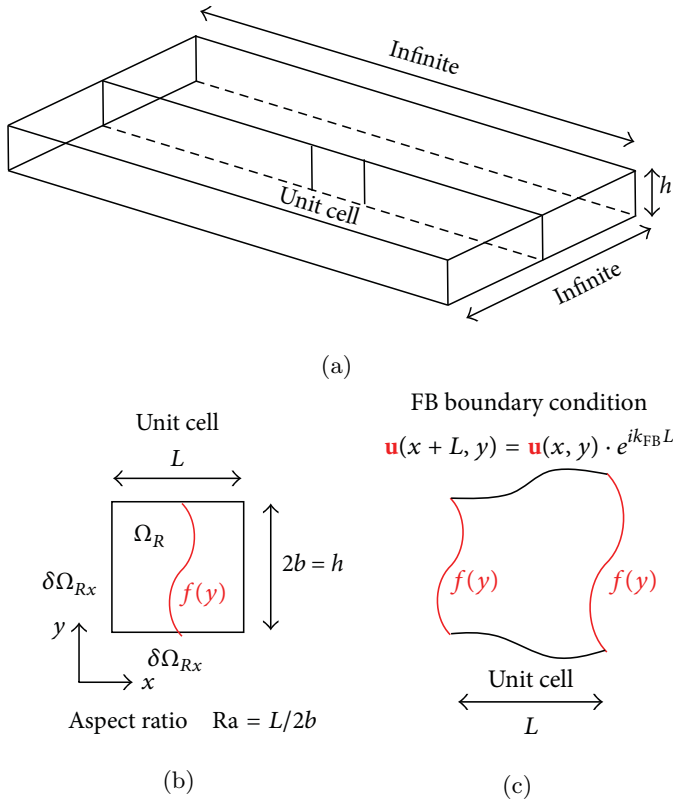


Figure 2.1: *(a) Infinite layer and the unit cell elected. (b) Computational domain (unit cell) properties and dimensions (x is the propagation direction). (c) FB boundary conditions applied to the laterals of the computational domain (unit cell) for a certain shape $f(y)$ [35].*

of a wave propagating in the x direction of a 2D domain is

$$\boldsymbol{u}(x, y, t) = f(y) \exp \mathrm{i}(kx - \omega t), \tag{2.1}$$

where k is the wave number, ω is the frequency, the spatial part of the solution can be extracted

$$\boldsymbol{u}(x, y) = f(y) \exp(\mathrm{i}kx). \tag{2.2}$$

Next, the displacement field at the left side of the unit cell is related to the displacement at the right side (Fig. 2.1), such that

$$\boldsymbol{u}(x + L, y) = f(y) \exp(\mathrm{i}kx) \exp(ikL) = \boldsymbol{u}(x, y) \exp(\mathrm{i}kL), \tag{2.3}$$

which is a system of equation that FB theory can provide the solution for. In this case, the wavenumber (k) is introduced as the complex Floquet component. The problem

can be solved using COMSOL Multiphysics® and the obtained eigenfrequencies for the specific Floquet components represent the dispersion curves. One benefit of this method is that it can be extended to multilayer materials without increasing the complexity of the problem. The red lines in Fig. 2.2 shows an example of the dispersion curves solved for a composite plate which is presented in **paper B**. In this figure the dispersion curves are shown in frequency and wave velocity domains which are derived from the results obtained in frequency and wavenumber domains. The curves show the number of wave modes and their phase velocities as a function of frequency.

2.2 Dispersion imaging

The dispersion behaviour of the GWs propagating in plates can also be depicted using experimental measurements or transient numerical calculations. This method is first introduced by Alleyne and Cawley [36] and later improved by other authors [37, 38] and it is based on measuring the wave response on the surface of a medium. The measurement is done at a number of equally spaced points in the propagation direction with a certain temporal sampling frequency [36]. Assuming $\boldsymbol{u}(x,t)$ is the measured response at several points, a temporal Fourier transform can be applied to convert the response from time-space to frequency-space domain. Next, applying a spatial Fourier transform converts the response to the frequency-wavenumber domain. This is shown as

$$H(k,\omega) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u(x,t)\mathrm{e}^{-\mathrm{i}(kx+\omega t)}\mathrm{d}x\,\mathrm{d}t. \tag{2.4}$$

Here, $H(k,\omega)$ is the magnitude in the frequency and wavenumber domains for all the spatial and temporal measurement points. Therefore, the propagating waves show larger magnitude and the dispersion curves can be depicted. The wave response can be determined by using numerical simulations (as carried out in **papers A and B**) or experimental measurements (**paper E**).

Using dispersion imaging and comparing the results with the calculated dispersion curves in the same material, it is possible to verify the results of the numerical model or the experimental data. Figure 2.2 shows an example of this comparison which is done in **paper B** to verify the numerical model. In this example, the high magnitude regions are obtained from a numerical calculation and are in an agreement with the dispersion curves.

3 Numerical simulations

Understanding the physical mechanisms of GW propagation in media is important to design robust and reliable SHM systems. This knowledge can be acquired by applying numerical simulation approaches as a support to experimental investigations. Moreover, the numerical models are particularly efficient for studying the effects of ambient conditions or parametric studies when numerous cases need to be investigated. The simulation results can be used to design and develop experimental set-ups or to quantify an SHM system. Available simulation methods for GW-based SHM are reviewed by Willberg et al. [39].

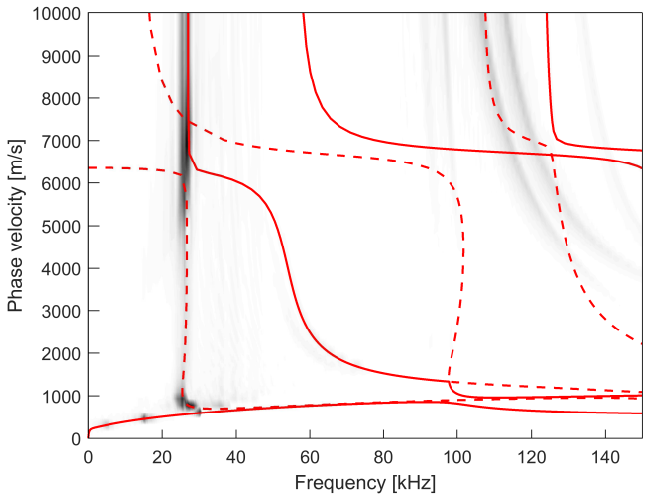


Figure 2.2: *A comparison of the dispersion curves of a composite plate and the finite element (FE) model's response in frequency-velocity domain (solid red lines are the asymmetric modes and dotted red lines are the symmetric modes).*

The methods are grouped as analytical, semi-analytical and numerical. Simulating the GW propagation using the numerical methods has typically less time efficiency compared to the other methods. However, due to their flexibility regarding the material properties and geometry, they have been a good choice to be applied on composite materials with complex geometries.

In case of simulating the GW propagation problem in a 2D isotropic medium, the scalar form of the wave equation is to be solved

$$a^2(u_{xx} + u_{yy}) + F(t) = u_{tt} + \gamma u_t, \tag{3.1}$$

where u is the out-of-plane displacement in the domain, a is the velocity of propagation in the isotropic medium, γ is a damping factor and F is essentially a transient excitation force. Equation (3.1) is discretized as

$$\begin{aligned} a^2\left(\frac{u_{i+1,j}^{(n)} - 2u_{i,j}^{(n)} + u_{i-1,j}^{(n)}}{\Delta x^2} + \frac{u_{i,j+1}^{(n)} - 2u_{i,j}^{(n)} + u_{i,j-1}^{(n)}}{\Delta y^2}\right) + F(t) = \\ \frac{u_{i,j}^{(n+1)} - 2u_{i,j}^{(n)} + u_{i,j}^{(n-1)}}{\Delta t^2} + \gamma\frac{u_{i,j}^{(n)} - u_{i,j-1}^{(n)}}{\Delta t}, \end{aligned} \tag{3.2}$$

where $u_{i,j}^{(n)}$ is the displacement of the node i and j at $t = n$. Δx, Δy and Δt are, respectively, x, y and time increments. By letting $\Delta x = \Delta y$,

$$u_{i,j}^{(n+1)} = (2-\Psi)u_{i,j}^{(n)} - (1-\Psi)u_{i,j}^{(n-1)} + \Omega^2\left(u_{i+1,j}^{(n)} + u_{i,j+1}^{(n)} - 4u_{i,j}^{(n)} + u_{i-1,j}^{(n)} + u_{i,j-1}^{(n)}\right), \tag{3.3}$$

where

$$\Omega = \frac{a\Delta t}{\Delta x} \tag{3.4}$$

and

$$\Psi = \gamma \Delta t. \tag{3.5}$$

Equations (3.3) can be solved numerically in every time increment. This type of numerical solution is a rapid way of simulation of GW propagation in a 2D medium and it has been used in **paper C** and **F** by a developed Matlab code. One draw back of this method is that including the complexity of the material or geometry is difficult. Other numerical methods, e.g. the spectral element method, can efficiently model the multilayer structure of composite materials by using high order polynomial shape functions [40, 41]. However in order to be able to model complex geometries using available commercial software, FE method is used to simulate the propagation of GWs. In the FE simulations, a general form of Eq. (3.1) is solved,

$$M\ddot{u} + K\dot{u} + Cu = F, \tag{3.6}$$

where M, K and C are respectively mass, damping and stiffness matrices of the medium. F is the transient force and u is the displacement. Equation (3.6) can be solved using FE commercial software. Leckey et al. [42] performed a benchmark study on simulation of GW propagation in composite laminates using different FE commercial software together with experimental comparisons. Their results show fair accuracy for all commercial codes. In this PhD project the FE simulations were performed using COMSOL Multiphysics® in **papers D** and **E** and Abaqus explicit in paper **A**, **B** and **F**.

Methods and applications of FE simulation of GW propagation have been reviewed by several authors [39, 43, 44]. They show that FEM can be used to study propagation of GWs in composite materials ([36, 45–50]), delamination detection on composite materials ([28, 51–55]), GW propagation in sandwich structures ([56–65]) and fault detection in structures with special applications ([66]). In this project the FE simulations are used to study application of GW propagation to delamination detection in composite laminates (**paper A**) and sandwich structures (**paper B**).

3.1 Convergence criteria

In the majority of the studies mentioned in the previous section, the FE simulation of GW propagation is performed using an explicit dynamic procedure. It is known that in this type of simulations temporal and spatial resolution should be small enough in order for convergence of the results to be reached. The criteria for the largest time step and element size are

$$\Delta t = \frac{1}{10 f_{max}}, \tag{3.7}$$

$$l_e = \frac{\lambda_{min}}{10}, \tag{3.8}$$

where Δt is the largest time step in explicit FE simulation, l_e is the largest element size, λ_{min} is the smallest wavelength and f_{max} is the highest frequency of importance [47].

The convergence criteria show that both element size and time step are functions of the frequency. In **paper A** a new convergence study is performed on FE simulation of GW propagation in a composite laminate beam. The major motivation for the study was that the frequency of excitation in the work was lower than in typical previous applications. Two more criteria are then introduced that should be taken into account together with Eqs. (3.7) and (3.8) (shown in **paper A**).

3.2 Homogenization methods

The convergence criteria presented in the previous section lead to large computational models in cases of large structures. Having an equivalent single layer model of the laminate for which the mechanical properties have been calculated using homogenization methods can reduce the size of the models. Classical laminate theory (CLT), which is derived from classical plate theory, calculates stiffness properties of the laminate by integration of in-plane stresses in the direction normal to the surface of the laminate [67]. This theory is used to study the effects of homogenization on GW propagation in composite laminates and sandwich structures in **papers A** and **B**. The CLT is used to calculate the extensional, coupling and bending stiffness of the laminate. Moreover, out-of-plane stiffness is calculated using the first order shear deformation theory (FSDT) which is an extension of the plate theory that takes into account shear deformations through the thickness of a plate [68]. By applying the homogenization methods, it is possible to reduce the complexity of the elements from solid to shell as has been done in **papers A, E** and **F**.

Several studies have previously been performed on modelling delaminations in composite laminates [69–72]. In order to reduce the complexity of introducing a delamination into the FE model, methods such as stiffness reduction can be used [73]. The stiffness reduction method is developed given that existence of defects in the materials causes a reduction of stiffness in the structure. Therefore, it is possible to model the defects by applying a local stiffness change in the material. In **paper A**, a stiffness reduction approach is introduced in an FE model of GW propagation in a composite laminate beam. The approach is based on three assumptions

$$t_d \approx t_l, \tag{3.9}$$

where t_d and t_l are the thickness of the delaminated region and the laminate itself,

$$[A_d] \approx [A_l], \tag{3.10}$$

where $[A_d]$ and $[A_l]$ are the extensional stiffness matrices of the delaminated region and the laminate itself. Assuming the angle brackets bring the parameters in a respective way, the second assumption is introduced as

$$\langle [B_d], [D_d] \rangle \approx \langle [B_{ls}], [D_{ls}] \rangle, \tag{3.11}$$

where $[B_d]$ and $[D_d]$ are the coupling and bending stiffness matrices of the delaminated region and $[B_{ls}]$ and $[D_{ls}]$ are the coupling and bending stiffness matrices of the larger

sub-laminate in the delamination region. Considering these assumptions, it is possible to calculate the coupling and bending stiffness matrices of the delaminated region

$$\langle [B_d],[D_d] \rangle = \begin{cases} \sum_{j=1}^{N} \int_{h_j}^{h_{j+1}} [Q_c]_j \mathrm{H}(z_k - z) \langle z, z^2 \rangle \mathrm{d}z & z_k \geq z_l \\ \sum_{j=1}^{N} \int_{h_j}^{h_{j+1}} [Q_c]_j \mathrm{H}(z - z_k) \langle z, z^2 \rangle \mathrm{d}z & z_k < z_l. \end{cases} \tag{3.12}$$

Here z_k and z_l are, respectively, the coordinate of the delamination and the coordinate of the mid-plane of the laminate in the thickness (z) direction and H is the Heaviside step function. The accuracy of the introduced approach is examined in **paper A**.

4 Transducer array design optimization

Applying multiple piezoelectric transducers instead of one, in some cases causes the generated waves to get the same phase and consequently have higher magnitude [74]. This characteristic is beneficial when it comes to SHM of composite structures with high damping properties. The high magnitude of the wave energy has to be related to the shape of the structure meaning that the amount of wave energy that reaches the edges of the domain has to be uniformly distributed. Therefore, the number and locations of the transducers should be changed according to the geometry. Different shapes of arrays have been suggested previously for different applications [75–78]. By using a time delay for the excitation of every transducer, the steering direction can be changed. Despite the differences between these configurations, all of them are used to maximize the magnitude of the GWs in a specific direction. This is beneficial in cases where a larger magnitude of the wave energy is needed in a certain direction. Since the aim of this work is to uniformly distribute the wave energy, the available array patterns cannot be used and new configurations have to be designed based on the shape of the geometry.

This topic is tackled in **paper C** by introducing an optimization model to design the arrays according to the shape of the domain. Optimization methods have been previously used for damage detection and identification using GWs and to reduce the number of transducers in an array [79–81]. However, no work has been done for designing the shape of the arrays for evenly distributing the wave energy in a domain.

4.1 Optimization problem

The Cartesian coordinates of the transducers in a 2D domain (x and y) are the design variables in the optimization problem. A Matlab code has been developed to simulate the propagation of scalar waves in an isotropic 2D domain. The displacement of the propagating wave has been calculated in several detecting points known as the "sensors". The distribution of the sensors in the 2D domain define the shape of the arbitrarily shaped geometry. The displacement recorded by the sensors has been normalized to obtain a signal amplitude. The wave energy is then calculated using the signal amplitude and is

used as a criterion to develop the optimization model

$$\begin{aligned} &\underset{\boldsymbol{X}_T, \boldsymbol{Y}_T \in \Omega}{\text{minimize}}\, D(\boldsymbol{X}_T, \boldsymbol{Y}_T), \\ &\Omega = \{X_L \leq x_i \leq X_U\,,\, Y_L \leq y_i \leq Y_U\,,\, i = 1, \ldots, \overline{N}\}, \end{aligned} \tag{4.1}$$

where the objective function is

$$D(\boldsymbol{X}_T, \boldsymbol{Y}_T) = \left(\frac{\max\limits_{n \in [1,M]} \{E_{\boldsymbol{T}}(S_n)\} - \min\limits_{n \in [1,M]} \{E_{\boldsymbol{T}}(S_n)\}}{\max\limits_{n \in [1,M]} \{E_{\boldsymbol{T}}(S_n)\}} \right)^2 . \tag{4.2}$$

Here $\boldsymbol{X}_T$ and $\boldsymbol{Y}_T$ are the optimization vector variables representing the Cartesian coordinates of the array T. $E_{\boldsymbol{T}}(S_n)$ is the energy of the wave generated from array T at sensor S_n. M and $\overline{N}$ are the total number of sensors and transducers, respectively. Furthermore, X_L, Y_L, X_U and Y_U are the lower and upper bounds on the x and y coordinates of the transducers in the array.

A nearly similar approach is also used to calibrate the time delay between the excitation of the transducers in the designed array. Using the time calibration, it is possible to improve the performance of the array. Assuming $\boldsymbol{\delta}$ is the vector of time delays for the array $\boldsymbol{T}$ and $E^{\boldsymbol{\delta}}_{\boldsymbol{T}}(S_n)$ is the energy of the propagated wave using the array in sensor S_n, a new optimization problem can be written

$$\begin{aligned} &\underset{\boldsymbol{\delta} \in \Psi}{\text{minimize}}\, C(\boldsymbol{\delta}), \\ &\Psi = \{0 \leq \delta_i \leq \delta t_U\,,\, i = 1, \ldots, \overline{N}\}, \end{aligned} \tag{4.3}$$

where the objective function is

$$C(\boldsymbol{\delta}) = \left(\frac{\max\limits_{n \in [1,M]} \{E^{\boldsymbol{\delta}}_{\boldsymbol{T}}(S_n)\} - \min\limits_{n \in [1,M]} \{E^{\boldsymbol{\delta}}_{\boldsymbol{T}}(S_n)\}}{\max\limits_{n \in [1,M]} \{E^{\boldsymbol{\delta}}_{\boldsymbol{T}}(S_n)\}} \right)^2 . \tag{4.4}$$

In these equations, δt_U is the upper bound on the time delay in the optimisation problem.

This optimisation model is presented in **paper C** and is applied on two examples followed by an experimental study. Further, it is used in **paper F** to design an array for a wind turbine blade geometry.

A genetic algorithm (GA) has been used to solve the optimisation problems. GAs were invented during 1960s as parts of evolutionary algorithms and inspired by the process of "natural selection" [82, 83]. In **paper C**, it is observed that the optimisation model is highly sensitive to the initial guess, therefore, a high number of populations are always used in the GA algorithm. The high population number helps to start the algorithm with a fairly good initial guess.

5 Experimental study

Experimental studies can be done as a support to validate the simulation models or for parametric studies to investigate the influence of different parameters. The experimental

work on GW propagation in media can be done using the two techniques of pitch-catch or pulse-echo. In the pitch-catch technique, two separate probes are used as transmitter and receiver. The technique works based on measuring the fluctuations in the transmitted wave due to a discontinuity which is located between the transmitter and the receiver. In the pulse-echo technique, however, ultrasonic pulses are transmitted into a medium and echo signals from scattering and reflections are measured using a receiver located at the same place as the transmitter.

Generation of the waves can be done using magnetostrictive or piezoelectric transmitters. The transmitters apply a force to the media on the contact surface. In **papers D** and **E**, the contact surface of the transmitter is located on the side of the plate, which generates mostly symmetric wave modes. In **paper C**, however, the contact surface is in the middle of the upper side of a plate which generates mostly asymmetric wave modes.

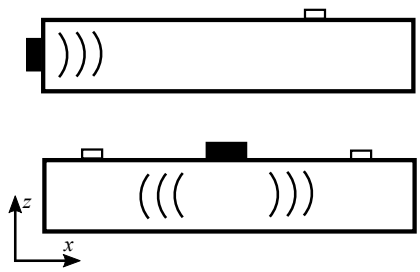


Figure 5.1: *The possible locations of the transmitters (the black squares) and the sensors (the white squares) on a plate.*

Measuring the signal due to the propagating wave is done using piezoelectric sensors. The sensors are coupled with the surface of the plate using a polymer glue. The location of the sensors can change based on the type of the experiment. In **paper D**, two sensors are located on the surface of the plate with a distance from the transmitter and create both pitch-catch and pulse-echo setup. By increasing the number of sensors and mounting them on the surface of the plate with equal distance between them, it is possible to receive more data. The data can then be used to understand the dispersion behaviour of the propagating wave using the dispersion imaging as done in **paper E**, see Fig. 5.2. In **paper C**, the location of the sensors are specially designed to validate a specific case study, see Fig. 5.3.

Using the experimental setup, it is possible to study the effects of different parameters such as ambient conditions or frequency of excitation on the propagating wave. Effects of surrounding temperature on the GWs propagating in a glass fibre plate is studied in **paper D**. The focus of this experiment was low temperatures, therefore the setup was located in a cold climate lab which makes it possible to reduce the temperature down to $-25°$ C.

Further, the frequency of excitation varied as a parameter in **papers D** and **E** to understand its influence. In **paper C**, several transmitters are used in order to understand the effects of their locations.

The main aim of **papers D** and **E** was to investigate the effects of ice accretion on

(a)

(b)

Figure 5.2: *(a) The experimental setup in a cold chamber used in* ***papers D*** *and* ***E****. (b) Locations of the array of accelerometers on the plate used in* ***paper E***

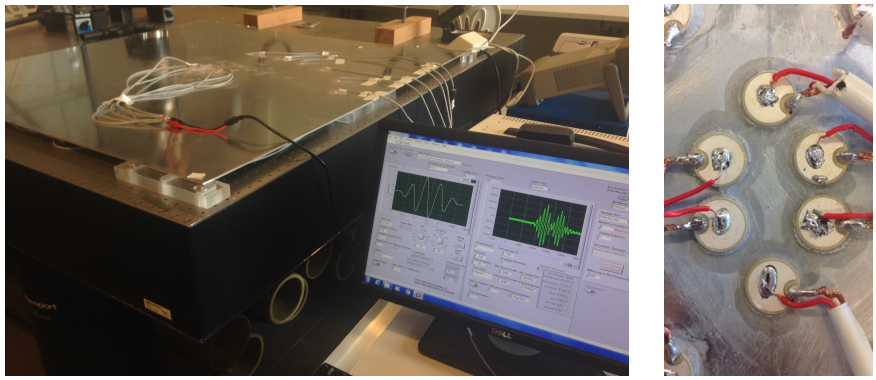
GWs propagating in composite materials. Therefore, ice needed to be manufactured on the used test plate. The ice manufacturing is done by spraying water on the surface under low temperature conditions in the cold climate laboratory, see Fig. 5.4. In **paper D** the thickness of the ice was varied as a parameter to understand its effects on the propagating wave.

Sending and receiving the electric signal should go through a data acquisition (DAQ) system. The sampling frequency that can be handled in the DAQ system should correspond to the frequency of interest in that experiment. As a role of thumb, the sampling frequency is considered at least 10 times larger than the frequency of interest. National Instrument DAQ systems are used for both transmitting and receiving the signal in all the experimental tests. The measured data go through a signal processing procedure as explained in the next section.

6 Signal processing

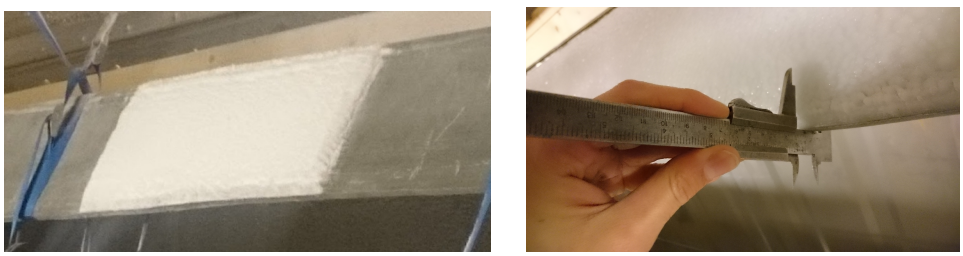
Data obtained from the experimental study or simulations should be modified and analysed to explain the behaviour or attribute of the propagating waves interacting with the defects. The measured data in the experimental study using piezoelectric sensors is an electric voltage. In simulations, however, the nodal displacements or accelerations have been calculated and used as the output data. By normalizing the measured data from experiment or simulations, it is possible to have a signal that corresponds to the propagating wave.

The modification and analysis of the received signal can be done using mathematical, statistical and heuristic formulations and techniques. The methods are developed according to comparisons in which a baseline signal is needed, or baseline-free. The importance of having a baseline-free signal processing (SP) approach is to be able to monitor the health



(a) *(b)*

Figure 5.3: *(a) The experimental setup using several transmitters and sensors and (b) a view of array of six transducers on the plate used in* ***paper C****.*



(a) *(b)*

Figure 5.4: *Manufactured ice on a glass fibre composite plate in the experimental study in* ***paper E****.*

of the structure at any point of the operation without any previous data. In this project, however, due to complications of the geometry and the structure, a baseline signal is always needed and the SP approaches are developed according to comparisons. A general form of such SP indices can be shown by

$$I = F(C(\alpha) - B(\alpha)) \tag{6.1}$$

where $C(\alpha)$ and $B(\alpha)$ are respectively the current and baseline signal in any domain. F is a SP function and I is the SP index.

The measurement of the signal is done in the time domain in which the amplitude is shown as a function of time. The SP approaches developed in time domain are based on changes in the amplitude of the signal, mode conversion due to reflections, Time-of-Flight (ToF) or phase shift [84–87]. Processing the signal in the time domain is a rapid way of analysing and it has been used in **papers A**, **B**, **D** and **E**. One drawback of applying SP approaches in time domain is that in case of high dispersion or multiple wave mode propagation, the signal of interest cannot be easily separated from the rest of the measured

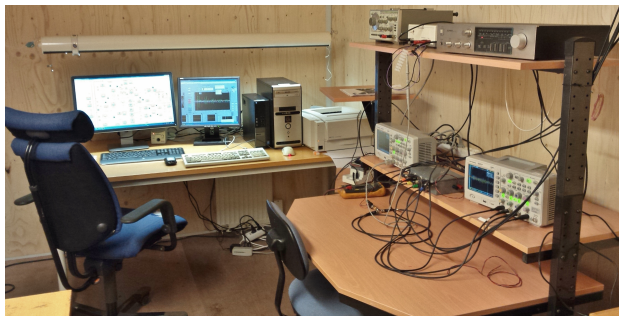


Figure 5.5: *The control room with DAQ systems used in the experimental study in* ***paper D*** *and* ***E****.*

signal.

A Fourier transform applied on the signal in the time domain converts it to the frequency domain. This is beneficial specifically in cases of high signal-to-noise ratio. A frequency based SP index (Eq. 6.2) using multi-channel sensors in **paper E** proved that location of accumulated ice on a composite plate can be detected.

$$Z = (\mid F(\omega_k) \mid - \mid F_0(\omega_k) \mid)^2. \tag{6.2}$$

In the equation above, $F(\omega_k)$ and $F_0(\omega_k)$ are the frequency response of the sensors for the current and baseline signals, respectively. Furthermore, in **paper A** the wave response in the frequency domain is examined to compare the behaviour of different GW propagation FE models.

The procedure of processing the signal can also be done in wavenumber domain which gives information about dispersion of the waves and changes of velocity of different wave modes with respect to the frequency [36, 88]. A spacial Fourier transform on the measured data at multiple sensors on the test object can convert it from the space to wavenumber domain. The accuracy of the results increases by increasing the number of sensors or the detection points. This method is used in **paper E** to measure the wave velocity on the plate and compare it to the case when ice is accumulated.

Some SP methods that help to understand the behaviour of the GWs are the energy based approaches [89–91]. The calculated energy corresponds to the energy of the dominant propagating wave mode. In **paper B** the wave energy is used as an index to understand the propagating mechanism of the GWs in a sandwich material. The corresponding wave energy is calculated at several detection points in time domain

$$E_{trans} = \int_{t_{start}}^{t_{end}} a^2(t)dt, \tag{6.3}$$

where $a(t)$ is the signal in time domain. The energy is calculated in frequency domain in **paper C** as an index to understand the distribution of propagating waves in the medium.

Different approaches of SP can be sensitive to different types of SHM. For example, in **paper E** it is shown that an icing index can be used to gain information about the

accumulated ice on a composite plate

$$II = \frac{\int_{t_{start}}^{t_{end}} \left[a(t) - a_0(t)\right]^2 dt}{\int_{t_{start}}^{t_{end}} a_0^2(t) dt} \tag{6.4}$$

where $a(t)$ and $a_0(t)$ are the current and baseline signals in time domain. One more example of these kind of indices is used in **paper A** where the Pearson correlation coefficient is shown to be sensitive to delamination size and location in composite laminate plates.

Filtering the signal obtained from an experimental measurement is part of processing the signal. Different types of filtering methods can be used depending on the type of the measurement. In the experimental work in **paper E**, the frequency of the noise is close to the excitation frequency. Here, the amplitude of the noise has been reduced by repeating the measurements and calculating the average of the amplitude of the signal. To further reduce the noise, a Gaussian filter is applied to the received signal

$$U_{x,F}(F) = U_x(f) e^{-K(f-f_n)^2} \tag{6.5}$$

where K is the coefficient which defines the bandwidth of the filter and f_n is the central frequency of the filter. $U_x(f)$ and $U_{x,F}(f)$ are, respectively, the signal in the frequency domain before and after filtering.

7 Summary of appended papers

- **Paper A:** The application of GW propagation to delamination detection is studied in this paper with the aim of applying it to a wind turbine blade model in future work. A novel approach is proposed to model delaminations by locally reducing the stiffness and it is implemented in a FE shell model. The approach is verified by comparing the results with the results of two existing approaches. Results show that the stiffness reduction approach gives reasonable accuracy for the primary wave modes and improvement in simulation time. Moreover, it is shown that new convergence criteria should be considered to simulate the GW propagation. Additionally, the Pearson correlation coefficient is introduced as a good criterion for delamination detection in such problems. All the conclusions are made when simulations are performed in the low frequency range and can be used to study GW propagation in large composite structures such as wind turbine blades.

- **Paper B:** In this paper, energy transmission of the GWs propagating in composite sandwich structures is investigated in a wide range of frequencies using numerical simulations. The effects of different potential defects on the GW energy transmission are explored in such structures. The accuracy of homogenization methods for FE modelling of GW propagation in sandwich structures is studied with the aim of reducing the computational burden of the simulations in the low range of frequencies.

A 2D FE model is developed and verified by comparing the results with the dispersion curves. In order to examine homogenisation methods, the homogenized stiffness matrices of the sandwich material and the laminate skin are calculated using classical laminate theory. Results show that core-skin debonding causes absence of wave energy leakage from the skin to the core material in that region in a specific range of frequencies. The results are also obtained for the delamination within the skin and compared with the healthy material. Finally, for the GWs in the low range of frequencies, it is possible to use the homogenization methods to create the FE models and reduce the solution time.

- **Paper C:** In this paper, a method is introduced to design the array of transducers in a way that wave energy is evenly distributed in a domain with any arbitrary shape. The approach is based on an optimization model and a genetic algorithm is used to solve the problem. First the optimization model is explained. Then two examples are solved using the method, first in an elliptically shaped domain, then in an arbitrarily shaped domain. In each example, several arrays are designed using different number of transducers. Finally, the method is validated using an experimental study on an aluminium plate. Results show that the method can be used to design the arrays of transducers for any arbitrarily shaped domain using different number of transducers.

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

- **Paper E:** Application of GWs for ice detection on composite structures is further studied by introducing a 3D computational model. The effect of temperature on the received signal which was found significant in **paper D** is analytically handled. 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 GWs are studied in time, frequency and wavenumber domains. New approaches are introduced in each domain for better understanding of the changes of the recorded signals. Moreover, an icing index is also proposed for ice detection giving output about the existence of ice on the composite plate. All the methods are examined using experimental measurements when ice is manufactured on the plate. Results show that application of GWs is a promising method for early ice detection and can be used in the wind turbine industry.

- **Paper F:** In this paper, application of GW propagation to defect detection in a full-scale wind turbine blade is investigated. The work is based on FE simulations of

GW propagation and the developed methods and conclusions in previous papers are used. The GWs are generated using an array of transducers which are specifically designed for the blade. The design approach is based on the optimization model developed in **paper C**. Delamination is modelled using the stiffness reduction approach developed in **paper A** in different regions of the blade. Results show that the array causes increase of wave energy so that the wave can propagate through the blade. Further, the propagating guided waves show different sensitivity depending on the locations of the delamination regions.

8 Conclusion and outlook

The overall goal of the research project is to investigate propagation of GWs in composite structures with focus on SHM of wind turbine blades. The work has been carried out by numerical simulations as well as experimental studies. Due to the large size of the structures, GWs that are used are in a low range of frequencies. Numerical simulations of GW propagation in composite materials are performed using FE methods. Application of homogenization methods on GWs propagating in such materials are investigated with the aim of reducing the computational time of the models. Effects of different types of defects on GWs propagating in composite materials and sandwich structures are studied using the FE simulations. To obtain high performance of GWs and overcome high damping of composite materials, a novel design optimization method is introduced. The method generates arrays of transducers for evenly distribution of wave energy in a domain with respect to its shape. The developed methods and conclusions are used to create a FE model of GW propagation in a full-scale wind turbine blade. Furthermore, the special problem of ice accumulation on wind turbine blades has been studied by analytical, numerical and experimental investigations. Several signal processing approaches are examined and introduced in every case study.

Based on the work that has been done in the project, the following can be concluded:

- To FE model the GWs in composite plates, the previously introduced convergence criteria are not sufficient and they have to be considered together with the new set of introduced convergence criteria in the low range of frequencies.
- Classical laminate theory can be used to homogenize the composite laminates and sandwich structures in FE models of GW propagation at low frequencies.
- Shell elements can be used for FE modelling of GW propagation in composite laminates at low frequencies for fundamental wave modes.
- Delamination in composite laminates can be efficiently modelled by the introduced stiffness reduction approach in FE simulations of GW propagation.
- Delaminated regions with a length larger than three times the wavelength of the propagating waves can be detected using a proper signal processing approach.
- Effects of debonding and skin delamination on GWs propagating in sandwich structures are nearly similar in the low range of frequencies.

- The optimization method that is introduced to design the arrays of transducers is capable of evenly distributing the wave energy in a domain with arbitrary shape.
- The optimization approach can be used to design an array for a wind turbine blade with the aim of maximizing the wave energy along it.
- Change of ambient temperature can significantly affect the propagating GWs in a composite plate and this effect needs to be handled in FE simulations.
- Accumulation of ice on a composite plate can affect the propagating GWs and reduces the velocity of the fundamental symmetric wave mode.
- The introduced signal processing approaches can give information about the severity of the delamination or amount of accumulated ice on the plates.

All the mentioned conclusions show that GWs in the low range of frequencies are capable of detecting defects or ice on composite materials. This potential, however, is limited to certain defect size, amount of ice, excitation frequency and signal processing approaches. Using GWs to develop multi-functional defect/ice detection system on wind turbine blades requires more experimental study in the future. One possible extension of the research is to use the numerical models, calibrated with an experimental setup, in an artificial intelligent algorithm to further develop detection criteria in complex structures such as wind turbine blades.

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