Application of low frequency guided waves to delamination detection in large composite structures: a numerical study

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Abstract
The aim of the current work is to identify the challenges in computational modelling of ultrasonic guided wave propagation in large structures and developing methods to overcome them. The work includes investigating the application of GW in composite laminates and sandwich materials with the aim of delamination detection. Moreover, phased array systems are introduced as a method of overcoming the negative effect of high damping properties in such structures. Propagation of GW in a wind turbine blade is studied as an example of large structure with the aim of defect detection. Results that show GW can be used as a potential tool for structural health monitoring of wind turbine blades.

1. Introduction

By the fast growth in usage of composite laminates in different engineering systems and particularly in large mechanical structures, the need for structural health monitoring (SHM) and non-destructive testing (NDT) of them is highly demanded. One way to fulfill the need is to make the classical methods of SHM and NDT compatible to work with the new types of materials. Guided waves (GW) are rapid, non-destructive and efficient tools in the fields of inspection which have been widely used for large metal structures. The main characteristic of GW which make them suitable for large structures is their ability to propagate along long distances which make it possible to scan a large region of the structures. This special characteristic, however, is affected by high damping properties of composite materials. Therefore application of GW to NDT and SHM of composite material has been limited mostly by the size of the structures. Despite the limitations, there have been previous studies on application of GW to aerospace and wind turbines industries [1, 2, 3]. The results of these studies show that GW has the potential of being used as an effective tool for SHM of such structures.

For further study of application of GW propagation in composite structures, the finite element (FE) method can be used. Leckey et al. [4] performed a benchmark study on comparison of numerical methods of simulation of GW propagation in composite laminates. They concluded that with proper configurations, the simulation tools are adequate for simulation of guided wave propagation in composite laminates. The demands for accurately simulating the GW propagation in composite laminates require smaller element size and time increment compared to other types of explicit dynamic simulations. This produces very large FE models when it comes to large structures which is difficult and in some cases impossible to solve. In order to overcome this obstacle new simplification methods need to be introduced to reduce the size of the FE models specifically for large structures.

Further, in order to overcome the effects of high damping properties of composite materials, the wave energy need to be amplified. Using multiple transducers to make the excitations instead of a single transducer, can provide the amplification [5]. Therefore, phased array systems specially designed for these types of structures could create sufficient amplification of the wave energy. Currently there are several types of designs for configuration of the transducers such as linear, rectangular or circular configurations [6]. Designing new traducer configurations for different structures can help to evenly distribute the wave energy in the whole structure.

The current work briefly introduces the methods of FE modelling of GW propagation in large structures with the aim of defect detection. Moreover, it discusses the effects of delamination on GW propagating in composite laminates and sandwich materials. Next, a method of design optimization for transducer configuration is introduced which can evenly distribute the wave energy in structures with arbitrary shapes. All the methods are used to study the application of GW propagation in a wind turbine blade as an example of large composite structure. Finally, conclusions are made and the future work within the field is mentioned.

2. Finite element modelling of GW propagation

FE modelling of guided wave propagation in composite materials can be done using commercial software. ABAQUS with explicit dynamic procedure is used to create the models and perform simulations with the assumptions of linear elasticity. Mass (M), damping coefficients (C), stiffness of the material (K) and external force (F) are defined in the model in order to solve the equation of motion (Eq. 1).

$$\mathrm{M}\ddot{u} + \mathrm{M}\dot{u} + \mathrm{C}u = F. \tag{1}$$

The FE models can be done either in 2D or 3D domains. The criteria for the largest time step and element size are

$$\Delta t = \frac{1}{10 f_{max}}, \tag{2}$$

$$l_e = \frac{\lambda_{min}}{10}, \tag{3}$$

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. Here two extra criteria should be considered together with Eqs. 2 and 3 and these are two elements in every ply and an element ratio of lower than 2:1. The excitation force is applied as an out-of-plane nodal force to a node. Since it is normal to the plate, the A0 wave mode is excited as the dominant wave mode. Due to high damping properties of composite materials, the wavelength of the propagated waves should be larger than in the typical applications of GW. Here the excitation frequency of 15 kHz is chosen. This low excitation frequency has negative effects on the accuracy of the detection system, however, it makes it possible to propagate the wave energy over longer distances.

2.1. Composite laminate

Composite laminates can be modelled in both 2D or 3D domains with layerwised or homogenized assumptions. 3D hexahedral elements with 8 nodes and 6 degrees of freedom (C3D8R) are recommended to discretize the geometry in a 3D domain [7]. Considering a method of homogenization, it is also possible to use the shell elements (S4R). Previously it is shown that using shell elements with the first order shear deformation assumption for out-of-plan forces can accurately predict the wave mechanism of the fundamental wave modes (A0 and S0) [8]. Here classical laminate theory (CLT) is used as a method of homogenization and extensional (A), coupling (B) and bending (D) stiffness matrices are calculated such that

$$\langle [A],[B],[D]\rangle = \sum_{j=1}^{N}\int_{h_j}^{h_{j+1}} [Q_c]_j \langle 1, z, z^2\rangle \mathrm{d}z. \tag{4}$$

For 2D models, elements with plane strain assumptions are used (CPE4R). These types of model are useful in order to avoid having 3D wave modes and get better understanding on the wave propagation mechanics. Since the geometry has a limited length, reflected waves are going to be produces when the incident wave hits the far end of the geometry. In order to avoid having unwanted reflections, absorbing layers using increasing damping (ALID) can be used on two side of the geometry [9].

In both 2D and 3D models which are produced using layerwised assumptions, the stacking sequence is applied by having local coordinate systems in every ply.

2.2. Sandwich structures

Sandwich structures with foam or honeycomb cores are typically part of the large structures. Therefore the propagation mechanism of GW need to be studied in such materials. The layerwised assumption for both 2D and 3D FE models can be used for simulation of GW propagation in sandwich structures. In some cases the core material can be homogenized into an isotropic layer without significant effects on the accuracy of the model [10]. A study on a type sandwich material which is common in the manufacturing of wind turbine blades reveals the GW propagation mechanism. By exciting the material for a wide range of frequencies it is observed that Lamb waves, leaky Lamb waves and Rayleigh waves are produced depending on the frequency of excitation. At low frequencies when only Lamb waves are produced, the propagation mechanism in the sandwich material is similar to a single laminate. Since the propagated wave follows the properties of laminate skin for these frequencies, it is possible to simplify the FE model by modelling a homogenized laminate skin instead of the sandwich plate. Similar to the composite laminate, shell elements with CLT homogenization method can be used to reduce the size of the model.

2.3. Delamination detection

Modelling a delamination in the FE model can be done by duplicating the nodes in the region of delamination and connecting them to the upper and lower elements. This method, however, is not applicable when it comes to homogenized models with shell elements. Therefore, a stiffness reduction approach (SRA) is proposed to model the delaminations. Here, three assumptions are made. Firstly, the loss in extensional stiffness of the delamination region is insignificant. Secondly, the propagated waves follow the properties of the larger sublaminate in the delamination region and finally, no thickness and mass change will be occurring in that region. Considering the assumptions it is possible to calculate the coupling ($[B^k]$) and bending ($[D^k]$) stiffness of the delamination region using

$$\langle [B^k],[D^k]\rangle = \begin{cases} \sum_{j=1}^{N}\int_{h_j}^{h_{j+1}} [Q_c]_j \mathrm{H}(z_k - z)\langle z, z^2\rangle \mathrm{d}z & z_k \geq z_l \\ \sum_{j=1}^{N}\int_{h_j}^{h_{j+1}} [Q_c]_j \mathrm{H}(z - z_k)\langle z, z^2\rangle \mathrm{d}z & z_k < z_l. \end{cases} \tag{5}$$

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.

Results show that both size and location of a delamination through the thickness is detectable using GW in the low range of frequencies (Fig. 1). Here Pearson correlation coefficient is used as a detection criterion which compares the current signal with the baseline signal (Eq. 6).

$$R_{xy} = \frac{1}{N-1}\sum_{i=1}^{N}(\frac{x_i - \mu_x}{\sigma_x})(\frac{y_i - \mu_y}{\sigma_y}), \quad (6)$$

where μ_x and σ_x are the mean and standard deviation of signal x and μ_y and σ_y are the mean value and standard deviation of signal y. N is the total number of samples in the discrete signals. Figure 1 shows that effects of delamination on the GW increases when the delamination size is larger than 3 times of the wavelength. Moreover, both solid and shell models follow the same pattern.

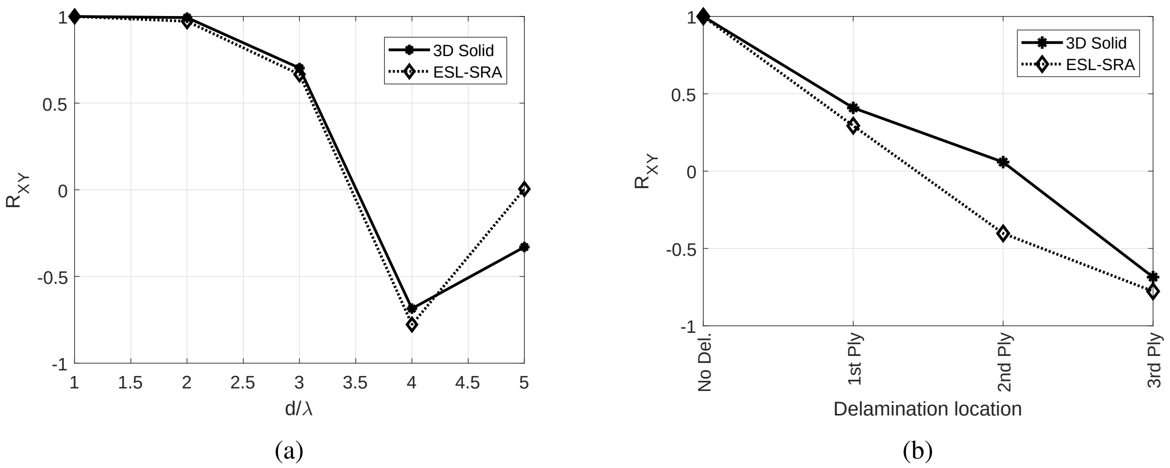

Figure 1: Effect of (a) delamination size and (b) location through the thickness on the Pearson correlation coefficient using the pitch-catch technique.

Effects of debonding between the core material and laminate skin in sandwich structures on GW are depending on the frequency of excitation. At low frequencies when only Lamb waves are generated in the sandwich material, the debonding between the core and the laminate skin acts similar to a delamination in composite laminates meaning that it creates reflected waves and changes the wave velocity. At higher frequencies when leaky Lamb waves are produced, the debonding prevents the wave energy from leaking into the core material and causes larger amplitude in that region (Fig. 2).

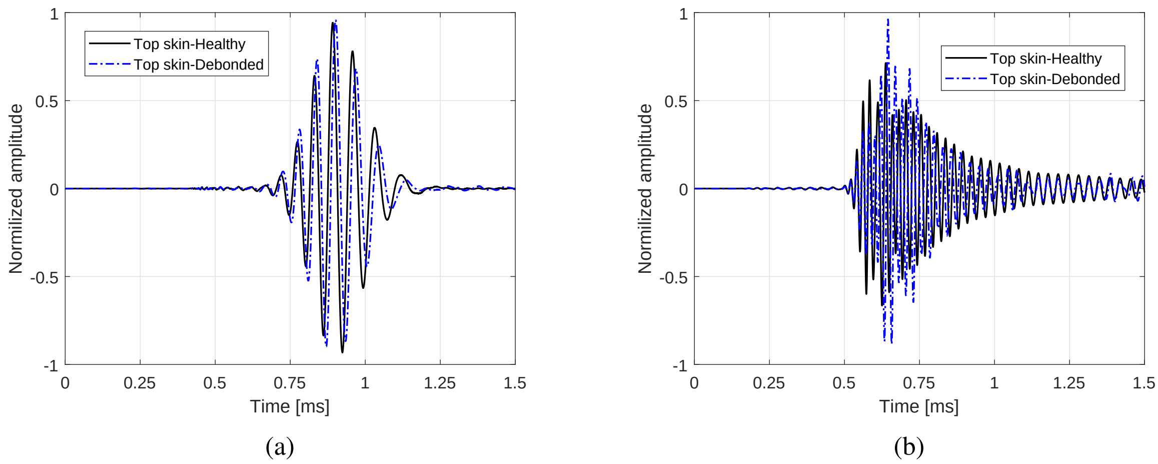

Figure 2: Response of the system in time domain for both non-defected and debonded plates for excitation frequencies of (a) 15 kHz (b) 40 kHz.

3. Phased array excitation system

As previously mentioned, one way to overcome the negative effects of high damping properties of composite laminates on GW propagation is to use an array of transducers for excitation. Previously, it is shown that different array design can be used for certain applications [11]. Here specific arrays are designed for certain shapes of geometries using a genetic algorithm. The aim of the optimization is to find array designs in a way that wave energy is equally distributed in the edges of an arbitrary shaped domain. Using this method it is possible to equally magnify the wave energy in all the directions. Since multiple transducers are used to excite the GW they can be used as receivers as well and no extra receiving sensors are needed.

4. Example: SHM of wind turbine blades

Using the mentioned methods, it is possible to create a FE model of a large composite structure to investigate the effects of delamination on GW propagation. Figure 3 shows the wave pattern when the blade is excited from a single point and a delamination is created. Here, creation of a reflected wave and mode conversion is observed. This preliminary results show that GW have the potential to be used as a SHM tool on wind turbine blades. Due to the complicated shape of the structure, a baseline signal is required to compare with the current signal.

5. Conclusion

Application of GW propagation in large composite structures is studied using finite element simulations. A method of stiffness reduction is introduced in order to model the delamination in composite laminates in a time efficient way. Furthermore, mechanism of GW propagating in sandwich structures is studied. Next, phased array excitation system is introduced to magnify the propagated waves. The approaches and conclusions can be used to create a computational model of a wind turbine blade as an example of a large composite structure. Results show that GW can be used as a potential tool of SHM of wind turbine blades.

Figure 3: Wave pattern in a wind turbine blade with no damage (top) and a delamination region (bottom).

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