Ultrasonic Rayleigh wave inspection of waviness in wind turbine blades: Experimental and finite element method

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Abstract
This paper presents the investigation of discrete, out-of-plane waviness in thick composite plates with applications to wind turbine blades. The investigation was carried out with the help of air coupled ultrasonics and a two-step procedure was framed to assist production line implementation. The first step involved detection of marcels, and the second step involved the characterization of these marcels with the help of an index called aspect ratio. A set of standardized samples with known aspect ratios were fabricated and used for this study. Finite element models were created to understand the wave propagation in wavy composite plates. All the experimental data was correlated with numerical B-Scans and conclusions concerning the method were made.

Keywords
blades, finite element analysis, plates (structures), Rayleigh waves, wave propagation, wind turbines, nondestructive evaluation

Disciplines
Aerospace Engineering | Materials Science and Engineering | Structures and Materials

Comments
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This article appeared in AIP Conference Proceedings 1430 (2012): 1911–1917 and may be found at http://dx.doi.org/10.1063/1.4716444.

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Citation: AIP Conf. Proc. 1430, 1911 (2012); doi: 10.1063/1.4716444
View online: http://dx.doi.org/10.1063/1.4716444
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1430&Issue=1
Published by the American Institute of Physics.

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ULTRASONIC RAYLEIGH WAVE INSPECTION OF WAVINESS IN WIND TURBINE BLADES: EXPERIMENTAL AND FINITE ELEMENT METHOD

Sunil Kishore Chakrapani¹, Vinay Dayal¹, Daniel J. Barnard¹, Aaron Eldal¹, and Ryan Krafka¹

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ABSTRACT. This paper presents the investigation of discrete, out-of-plane waviness in thick composite plates with applications to wind turbine blades. The investigation was carried out with the help of air coupled ultrasonics and a two-step procedure was framed to assist production line implementation. The first step involved detection of marcells, and the second step involved the characterization of these marcells with the help of an index called aspect ratio. A set of standardized samples with known aspect ratios were fabricated and used for this study. Finite element models were created to understand the wave propagation in wavy composite plates. All the experimental data was correlated with numerical B-Scans and conclusions concerning the method were made.

Keywords: Air-Coupled Ultrasound, Fiber Waviness, Thick Composites, Wind Turbine Blades
PACS: 43.35.Zc, 43.35.Pt

INTRODUCTION

Emphasis on wind power has increased in the past decade due to the hike in oil prices and the need for a more reliable and environment friendly energy source. This increases the demand of wind power systems to be installed on shore and off-shore. A wind power system typically consists of wind turbine blade, which is the primary component, the tower to mount the blades, gearbox and generator to convert the mechanical energy into electrical energy. The wind turbine blade is of specific interest from an engineering point of view, due to the multi-material, multi-layered construction of the blade. Most of the blades manufactured today use fiber-glass reinforced composite for its primary structures such as the spar cap, trailing edge, skin etc. A strict quality control has to be enforced, to maintain quality of the blades.

The use of non-destructive testing to detect defects such as delaminations, lack of infusion, waviness in generic composite plates has been shown earlier [1][2][3]. These can be extended to wind turbine blades, since majority of the structure is fiber glass composite. Some of the current methods employed to test wind turbine blades are high intensity light inspection, contact ultrasonics and thermography. Out of the defects mentioned earlier, lamina waviness is of particular interest, since it difficult to detect and determine its severity.
Waviness can be defined as geometric distortion of lamina in a localized region. Although only physical distortion of fibers occurs, a significant decrease in mechanical properties occurs in the localized region. The decrease in properties is a function of fiber shear angle and has been calculated earlier by Hsiao & Daniel [4]. Severity of waviness can be defined with the help of aspect ratio, which is a measure of the height and width of the wave. This has been used earlier by Mandell [5] in the form of wave severity. Dayal [6] studied stress wave propagation in wavy laminates and was able to show that the periodicity of waviness can be measured by performing C-Scans. Wooh and Daniel were able to show that ray tracing technique is a feasible method to understand the physics of waviness.

This paper presents a method to detect and characterize discrete, out of plane waves using non-destructive evaluation. A scanning technique using air coupled ultrasonic transducers was developed. The air medium makes this technique non-contact, and eliminates variability of thickness of the coupling gel. Inspection was performed on an engineered trailing edge (TE) sample with four waves of different aspect ratio and at two different depths. Rayleigh wave was generated on the TE sample using air coupled transducers of 200 KHz frequency. The detected waves were quantified in terms of aspect ratio with the help of changes in velocity (damage index) while traversing over the wave.

**OBJECTIVE**

The main objective of this research is to detect discrete, out of plane waviness in trailing edge sections of wind turbine blades and find a method to quantify the wave in terms of aspect ratio. To achieve this objective a two step method was developed.

**Step 1:** Detect the waves in the section by performing large area scans using air coupled ultrasonics

**Step 2:** A high resolution B-Scan is performed in the localized region of the wave to determine the aspect ratio.

**SAMPLES USED AND EXPERIMENTAL SETUP**

For all the experiments, real trailing edge samples were fabricated with waves of different aspect ratios. Epoxy wedges of desired aspect ratio were cast out of molds and inserted into fabric during the infusion process. The same set of waves was placed at a different depth to study the effect of depth on detection and characterization. TE samples containing 7 waves of aspect ratio ranging from 4 to 20 and at two different depths, i.e. 2 mm and 6 mm from the top surface were fabricated. The waves were placed perpendicular to the direction of the unidirectional glass fiber fabric used for fabricating the sample. The samples used are listed in Table 1.

<table>
<thead>
<tr>
<th>Wave</th>
<th>Aspect Ratio</th>
<th>Depth in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>I</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>J</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>K</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>M</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>N</td>
<td>10</td>
<td>6</td>
</tr>
</tbody>
</table>
A pair of 200 KHz air coupled Ultran transducers was used for generating the Rayleigh wave on the surface of TE samples. The schematic of the experimental setup used is shown in Figure 1. A QMI SONDA 007-CX was used to drive the transducers. Since the system was capable of self triggering and data transfer via GPIB, it acted like a standalone system. For scanning, an X-Y-Z scanner was used, which could index in one direction and scan in the other direction. The transducers were oriented at an angle at which a surface wave, also known as Rayleigh wave was generated. A constant distance of 100 mm was maintained between the transducers.

RESULTS

A single sided pitch catch approach was used for detection of marcel. The sensitivity of Rayleigh wave to buried flaws is given by $1\lambda$, which is the wavelength of Rayleigh wave. The sensitivity was theoretically found to be 10 to 12 mm. Since the trailing edge has two shells bonded together, one scans on either side would reveal the presence of waviness. A single sided inspection setup as shown in Fig. 2 was fabricated and tested on the engineered sample.

All the waves reported in this paper are downward pointing marcel. The effect of orientation of the wave was already reported [7]. The downward pointing wave increases the ultrasonic wave amplitude and decreases the velocity of the ultrasonic wave. Although previous investigation showed that detection of waviness was possible with a single sided approach [8], depth and variation of velocity of the ultrasonic wave was not addressed. To refine the method, a standard set of TE sample which have 7 waves of 4 different aspect ratio and 2 different depths were fabricated. The range of aspect ratio considered was from 4 to 20. Since the severity of the wave scales as a function of thickness of the plate, this range of aspect ratio was chosen. Ultrasonic wave propagation direction is parallel to the direction of waviness, i.e. ultrasonic wave propagation direction is perpendicular to the direction of fabric.

The three axis scanner was used to scan the TE sample, and the C-Scan results are shown in Figure (2). An increase in amplitude of the ultrasonic wave was observed in the localized region. The single sided approach was able to detect all the 7 waves, at both 2mm and 6 mm depth.

CHARACTERIZATION OF WAVINESS

The second objective is to characterize the detected waves in terms of its physical dimensions or aspect ratio. Although detection tells the presence or absence of a wave, the
severity of the wave is important to take a decision on the rejection or acceptance of the blade. Lower aspect ratios will have a bigger impact on the structural integrity compared to higher aspect ratios.

A high resolution B-Scan was performed on the vicinity of the detected wave. The region containing no wave is termed as good region, and wavy region termed as defective region. By performing a scan in this region, one can obtain the amplitude and time of flight information. Since the Rayleigh wave velocity decreases while traversing over the wave, a damage metric based on time of flight information was developed. The difference in time of flight between the good region and defective region is called as Damage Index (DI) number. The DI number is used to characterize an unknown wave.

**FIGURE 2.** C-Scan images of 7 different waves.
FIGURE 3. Plot of aspect ratio and damage index number.

The results of the B-Scan data for waves places at 2 mm is plotted in Figure (3), as damage index vs. aspect ratio. A particular trend can be observed from the plot. As the aspect ratio increases the DI number increases. As the aspect ratio approaches 20, the sensitivity decreases since a wave of aspect ratio 20 would be very flat in a 30 mm thick composite plate. With the help of this plot, one can perform a B-Scan on an unknown wave, and fit the DI number in this curve to determine the range of aspect ratio. Although the waves placed at 6 mm could be detected, they could not be reliably quantified. Since maximum sensitivity of Rayleigh waves occurs closer to the surface, characterization of 6 mm waves was difficult.

FINITE ELEMENT ANALYSIS

To understand the physics behind elastic wave propagation in wavy laminates, finite element method was used. A 2-D model of a generic, unidirectional glass fiber composite plate with discrete out of plane waviness was modeled as shown in Figure (4). Instead of modeling as a laminate layers, a two layer model was created. The model consists of a layer of laminate with a layer of epoxy in-between two layers of laminate. Waviness was modeled by geometrically distorting the fibers in Y direction. 2D PLANE 183 elements with plane strain condition were used to represent a thick structure in Z direction. The material properties used for simulation are listed in Table 2.

FIGURE 4. Finite element 2D model of waviness.
FIGURE 5. Numerical A-Scan of Rayleigh wave.

TABLE 2. Material properties of laminate and epoxy used for numerical modeling.

<table>
<thead>
<tr>
<th>Properties of Laminate</th>
<th>Value in GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$</td>
<td>44.68</td>
</tr>
<tr>
<td>$E_y$</td>
<td>6.90</td>
</tr>
<tr>
<td>$E_z$</td>
<td>6.90</td>
</tr>
<tr>
<td>$\nu_{xy}$</td>
<td>0.280</td>
</tr>
<tr>
<td>$\nu_{yz}$</td>
<td>0.355</td>
</tr>
<tr>
<td>$\nu_{xz}$</td>
<td>0.280</td>
</tr>
<tr>
<td>$G_{xy}$</td>
<td>3.06</td>
</tr>
<tr>
<td>$G_{xz}$</td>
<td>3.33</td>
</tr>
<tr>
<td>$G_{yz}$</td>
<td>3.109</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1990 Kg/m$^3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties of Epoxy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$</td>
<td>3.0</td>
</tr>
<tr>
<td>$\nu_{xy}$</td>
<td>0.38</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1200 Kg/m$^3$</td>
</tr>
</tbody>
</table>

As an initial step to optimize the frequency, wave propagation was performed at 200 KHz and 100 KHz. The waveform was collected for 200 microseconds. A numerically simulated A-Scan of the Rayleigh wave is shown in Figure (5). A time of flight measurement showed that the numerical and experimentally observed velocities matched well. It was also observed from numerical simulations that amplitude of the primary mode increases with increase in distance of separation, and a secondary mode generation was possible.

Numerical B-Scans were performed over the model to compare numerical and experimental results. B-Scans also helped in optimizing the frequency of excitation for experiments and were performed at 200 KHz and 100 KHz. The B-Scan images are shown in Figure (6.a) and Figure (6.b). The 100 KHz B-Scan shows changes in amplitude and time of flight, but the TOF shift is very minimal. Compared to the 100 KHz, the 200 KHz shows much higher sensitivity to waviness, and the amplitude change and shift in TOF is much more prominent. With the help of these results, 200 KHz was used for all experiments and numerical simulations.
FIGURE 6. Numerical B-Scan images of (a) wavy laminate at 100 KHz, (b) wavy laminate at 200 KHz.

The same procedure was repeated for different aspect ratios, but no significant change in velocity or amplitude was observed. Although time of flight change is not appreciable, the ability to map the change in velocity by the numerical model was considered as a first step. With a refined model, much better sensitivities can be achieved.

CONCLUSION

A non-contact method of NDE for investigating waviness in wind turbine blades has been developed. Sensitivity to detection and characterization of waviness was high. Since this method incorporates the use of velocity along with amplitude, false alarms can be eliminated. Furthermore, the effect of depth on Rayleigh wave propagation will be studied in detail, and a refined numerical model to study the effects of elastic wave propagation in wavy laminates will be analyzed.

REFERENCES