Characterization of waviness in wind turbine blades using air coupled ultrasonics

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Abstract
Waviness in glass fiber reinforced composite is of great interest in composite research, since it results in the loss of stiffness. Several NDE techniques have been used previously to detect waviness. This work is concerned with waves normal to the plies in a composite. Air-coupled ultrasonics was used to detect waviness in thick composites used in the manufacturing of wind turbine blades. Composite samples with different wave aspect ratios were studied. Different wavy samples were characterized, and a three step process was developed to make sure the technique is field implementable. This gives us a better understanding of the effect of waviness in thick composites, and how it affects the life and performance of the composite.

Keywords
composite materials, nondestructive testing, optimisation, data acquisition, nondestructive evaluation, QNDE, Aerospace Engineering

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

Comments
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This article appeared in AIP Conference Proceedings 1335 (2011): 956–962 and may be found at http://dx.doi.org/10.1063/1.3592041.
CHARACTERIZATION OF WAVINESS IN WIND TURBINE BLADES USING AIR COUPLED ULTRASONICS

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ABSTRACT: Waviness in glass fiber reinforced composite is of great interest in composite research, since it results in the loss of stiffness. Several NDE techniques have been used previously to detect waviness. This work is concerned with waves normal to the plies in a composite. Air-coupled ultrasonics was used to detect waviness in thick composites used in the manufacturing of wind turbine blades. Composite samples with different wave aspect ratios were studied. Different wavy samples were characterized, and a three step process was developed to make sure the technique is field implementable. This gives us a better understanding of the effect of waviness in thick composites, and how it affects the life and performance of the composite.

Keywords: Air-Coupled Ultrasound, Fiber Waviness, Thick Composites, Wind Turbine Blades

PACS: 43.35.Zc, 43.35.Pt

INTRODUCTION

With the increase in attention towards renewable source of energy, the U.S government has projected that by 2020 about 20% of its energy sources will be from wind energy. This has led to increase in number of wind turbines being produced, expansion of grid size, and designing bigger turbine blades to efficiently harvest energy. These factors stress on the need for lighter blades, and this directs us towards research for increased use of composite materials. As the case with composites and big structures, testing for defects both onsite and offsite becomes very difficult. This brings about the need for better NDE methods to be implemented and standardized. A general composite turbine blade uses more composite in certain areas such as the spar cap, trailing edge and leading edge. Manufacturing defects are likely to rise in these locations. Moreover, since these are the major structural members of the blade, the need for quality inspection in these areas would be vital. The NDE methods currently employed for this purpose maybe contact ultrasonics, radiography and/or infrared thermography. But these methods cannot be implemented on-site, and are time consuming. Some of the attributes of an efficient testing system would be:

- Quick and efficient scans
- Ability to scan large areas
- Possibility of quantizing the defects
- Simple scanning setup for on-site inspection
One method which encompasses all the above attributes is air-coupled ultrasonics. With a well optimized setup, the time taken per scan is considerably less. The setup required for this purpose is also simple and results can be read directly without the help of trained labor. Air couple ultrasonics uses the principles of ultrasonic wave propagation, but the only difference is the coupling medium which is air instead of water or gel. Air medium makes this method a completely non-contact method, and helps in eliminating the mess created by gel or water. It also makes both the step and the scans faster. Waviness in composites has been studied for more than 30 years, and still there is considerable amount of research being done on this topic. Waviness has been characterized in terms of material properties, localized geometric distortions. The effect of waviness has also been studied by mechanical testing of samples with engineered waves. Typically waviness can be classified into two types, first the in-plane waviness where the fiber distortion is in the plane the plate, i.e. X-Z plane. The second type of waviness is out of plane waviness where the distortion of fabric exists through the thickness of the laminate, i.e. in the X-Y plane. These waves can be totally intrinsic i.e. within the laminate and do not have any surface effect or they could protrude out of the surface and result in surface waviness. The intrinsic waves generally have a flat top and bottom surface, and are relatively more difficult to detect compared to surface waviness. A typical wave can be defined as geometrical distortion of fibers normal to the fiber direction. The curving of fibers creates a geometric distortion, but typically we find a resin or epoxy rich area under the wave which is the root defect. Out of plane waviness was investigated in this paper. All the waves engineered were intrinsic waves without any surface waviness.

As the thickness of the resin region increases, the height of the wave increases. Waviness is not just attributed to geometrical distortion but also a local change of material properties. This work was shown previous by Hsiao & Daniel [1]. As described in this paper, the localized region is orthotropic with 9 independent constants. For the entire laminate, the Young’s modulus, and compressive strength degraded with increase in amplitude of waviness. But the most vital amongst these concerns would be the fatigue life which decreases by a factor of $10^3 - 10^3$ as shown by Murri [2]. All the previous work in this area shows the detrimental effects of waviness in composites.

**OBJECTIVE**

The main objective of this research is to detect non-uniform & discrete waviness in thick composite sections of wind turbine blade and find a method to quantify the wave in terms of dimensions. Additionally this system has to be field implementable. A three step approach was framed to reach our objectives and the steps are as follows:

Step 1: Detect the waves in the section using ultrasonics

Step 2: Quantify the size of the wave

Step 3: Check with the manufacturer’s specification of the wave to see if it falls within the acceptable limits.

Immersion or contact ultrasonics gives good result for detecting waviness, but as mentioned earlier, air coupled ultrasonics was experimentally found to give more reliable results along with easier and faster scans. Hence it was used for the detection and characterization. The size of the wave was quantified by the aspect ratio which is defined as:

$$Ar = \frac{L}{a}$$
FIGURE 1. Aspect ratio.

The span of the wave is defined as “L”, and the height of the wave was defined as “a” as shown in Fig. 1. The aspect ratio is a/L.

SAMPLES USED AND EXPERIMENTAL SETUP

For all the experiments real trailing edge samples were made according to the exact specification, and engineered waves were created in them. Wavy wedges of epoxy were cast with the desired aspect ratio. These wedges were placed in between the dry fabric and the vacuum resin infusion was performed. The top and bottom surfaces were kept flat so that the intrinsic waves could be produced. 120KHz focused transducers made by QMI were used for scanning. The QMI SONDA 007-CX was used to drive the transducers at a PRF of 100 KHz. Since the system was capable of self triggering and data transfer via GPIB, it acted like a standalone system. The focal length of the transducers is ideally 1.5 inches. For scanning, an X-Y-Z scanner was used, which could index in one direction and scan in the other direction. The type of scan used for this purpose was the single sided scan which generates Rayleigh waves. This is explained in detail in the following chapters.

RESULTS

Single Sided Inspection: Rayleigh Waves

With the need for a faster and more sensitive type of scan, Rayleigh wave was used to detect waviness. By inclining the transducers at an angle beyond the 2nd critical angle, Rayleigh wave was generated on the surface of the sample. The sensitivity of Rayleigh wave to buried flaws is given by 1/λ which is the wavelength of Rayleigh wave. The sensitivity was theoretically found to be 15mm. Since the trailing edge has two shells bonded together, two scans on either side would reveal the presence of waviness. A single sided inspection setup as shown in Fig. 2 was made, and put to use on the engineered sample.

FIGURE 2. Single sided angled air coupled inspection using Rayleigh waves.
For the first few scans, the distance of separation between the probes was kept at a constant value of 4 inches. C-Scans results are shown in Fig. 3.

The signal amplitude increases as the scan was performed over the waves. This can be attributed to the geometric distortions which cause the ultrasonic wave to travel along the wavy fibers. When the transducers move over the wavy fiber, more energy is dissipated in the direction of the fiber. A through transmission scan was performed to compare with single sided inspection results. The single sided inspection showed higher sensitivity compared to through transmission. Moreover the setup is relatively simple and it took less time to perform the scan. With this in mind, further optimization of the distance of separation was done.

As we see in Fig. 4, even at a distance of 8 inches, with a small increase in gain, the signal amplitude remains constant, and the defect can be clearly identified. This helped to minimize the time for each scan while maintaining uniform sensitivity. From the above results it is clearly evident that this method can be used for detection of waviness in composite sections of the wind turbine blade. The scan time for a 16 x 16 inch section was 1 hour for the through transmission mode, where the scan is performed at every point. With 5 inch separation, the Rayleigh wave mode consumes little more than 15 minutes. While 8 inch separation, it was reduced to less than 7 minutes. The area of interrogation is much larger in this mode of interrogation. As the initial objective was defined, a reliable detection method which uses air coupled ultrasonics, with a simple setup, with higher sensitivity, field implementable and short scanning time was developed.

CHARACTERIZATION OF WAVINESS

Along with the detection of wave it is desirable to quantify the size of the waviness. This is important for the manufacture as a go/no go measure could be developed where an aspect ratio could be accepted or rejected. The approach is as follows:

![Figure 4. C-Scan result with waves for different distance of separation.](image)
- Detect the location of a non-uniform, discrete wave with the help of air coupled ultrasonics.
- Use either contact or non-contact ultrasonics in the localized region to quantify the wave in terms of aspect ratio.

This would be a field implementable type system. For lab experiments, calibration samples with discrete waves of known aspect ratios were created, and used for experimentation. Goal was to find a correlation between aspect ratio and a parameter in the scan, so that the system or method can be calibrated.

EXPERIMENTS & RESULTS OF CHARACTERIZATION

The approach towards the scan was a variant of air coupled through transmission scan which utilizes beam steering technique to quantify the aspect ratio. The setup for this type of scan is similar to a through transmission scan, but instead of moving both the transmitter and receiver simultaneously, the transmitter remains stationary, and the receiver collects data, and the transmitter increments by $\Delta T$ for every step. The setup is shown schematically in Fig. 5, where $R_1$ is the length of sample, and $L$ is the span of the wave in the sample. The scan procedure is as follows:

- Step 1: The transmitter is positioned at its initial position at $T_s$, and the receiver is positioned at $R_s$.
- Step 2: The receiver moves from $R_s$ to $R_f$ and collects data while the transmitter is transmitting at $T_s$.
- Step 3: the transmitter moves by a small increment of $\Delta T$ along the line $T_s - T_f$ and the receiver moves from $R_f$ to $R_s$. The data collected during this B scan is stitched with the previous data and the process is repeated for $n$ sub steps till $n \times \Delta T = T_t$.

Ideally, without any waves the scan would look as shown in Fig. 6. A high intensity band which travels diagonally would be expected. When the two transducers are opposite to each other the signal amplitude is maximum and as they move away the signal amplitude drops.

FIGURE 5. Through transmission scan setup for characterizing waviness.
When the same scan was performed over a wave of know aspect ratio (18), the scan obtained is shown in Fig. 7.

The band tends to narrow down as the transmitter approaches the middle of the wave, and at 25% and 75% of the length of the wave, two high intensity regions are observed. This phenomenon can be explained with the help of beam steering by the distorted fibers. A ray travel diagram is shown in Fig. 8 at roughly 25% and 75% of the length of the wave.

As shown in the figure, when the transmitter is at 25% of the length, the geometrical distortions of the fiber tend to steer the beam at an angle normal to fibers. Hence the steered beam ends up at an offset to the original position. The same phenomenon occurs at 75% of the length. This is clearly evident in Fig. 7, with the two bright spots on either side of the diagonal band. To confirm the effectiveness of the method, another scan was performed on a sample of different aspect ratio of 14. The scan result as shown in Fig. 9, the curving of the band can be seen, and the two high intensity spots are much closer to the diagonal band compared to the previous aspect ratio.
This can be explained as follows. If the span of the wave is constant and the height of the wave is increased to get a lower aspect ratio, then beam steer angle is decreases with respect to normal, and therefore the spots come closer to the main diagonal band in the scan. From these results we see that we can use this method for characterizing the wave. The distance between the spots can be related to the aspect ratio. The drawback of this method is that its field applicability is doubtful. But nevertheless this type of characterization helps us to determine the aspect ratio in a controlled environment. Optimization of this method could lead us to better results.

CONCLUSION

This paper reports the initial results in the investigation of single sided inspection of composite wind turbine blades for waviness. The approach is believed to hold potential for making a field implementable system. Sensitivity to waviness was higher compared to other methods, and characterization of waviness was demonstrated with the help of aspect ratio. The field adaptability of this system, coupled with the cost effectiveness and speed of scans makes it a very preferable method for NDE of wind turbine blades compared to other methods.

REFERENCES