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Imaging defects in laminate composite plates using focused shear waves generated by air-coupled transducer

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ABSTRACT

This research develops a nondestructive evaluation (NDE) technique to obtain images of two types of defects, delamination and debonding, in a thick laminate composite plate as a laboratory material system for wind turbine blades. The technique uses focused shear waves which are generated and detected by a set of noncontact, air-coupled ultrasonic transducers. The noncontact nature of the air-coupled method facilitates rapid scanning/inspection of large composite structures. Ray-tracing simulations are performed which visualize the focusing behavior of the focused shear waves in the specimen, from which the experimental parameters are determined. The proposed focused shear wave technique is compared with a Lamb-wave based technique, showing that the present technique is more appropriate for direct imaging of these defects. The obtained images of delamination and debonding defects agree well with the estimated defect locations and dimensions. This demonstrates the feasibility of further developing the present technique for specific field applications in wind turbine blades.

1. Introduction

Wind energy is a renewable source of energy that has enormous potential; its worldwide potential amounts to 400 terawatts which is about 20 times more than the need for the entire human population [1]. Due to the additional economical advantages such as low operational cost, space-efficiency, and decreasing price, many countries around the world have a plan to increase the portion of wind energy in their energy portfolio. This has led to investments in this area and rapid development of wind turbine technology.

The size of the wind turbine continuously increases for higher harvesting efficiency [2]; in fact, the wind turbine blades are the biggest man-made composite structure. These are constructed by bonding sub-structures where the upper and lower composite shells are adhesively bonded at the leading and trailing edges, containing a spar that is also bonded to the shells as a major load carrying component. Debonding at bonding areas is one of the most typical and critical types of damage, especially when this occurs inside the structure, thus being invisible. Another one is the delamination which typically is either from the manufacturing process or generated by a low velocity impact. In wind turbine blades, delamination in skin layer and the main spar flanges are of important damage types. This research considers evaluating both of these damage types in a model composite structure. Numerous on-line monitoring [3,4] and off-line inspection techniques [5,6] and other methods based on vibration measurements [7] and statistical signal processing [8] have been reported. On-line monitoring techniques such as the acoustic emission monitoring and Lamb-wave technique based on permanently attached sensor patches have the advantage, only if the permanent sensor attachment is practically realizable, that damage can be detected in real time so that the structure condition can be continuously monitored. However, these on-line monitoring techniques require modification of the blade structure for installation of the sensors and wires and long term sustainability of attached sensors is yet to be validated. Off-line NDE techniques require stopping the operation and also needs a robot system [9] that carries the transducers, signal generator, and data acquisition system and performs the inspection. Nonetheless, the off-line NDE systems are much more reliable and provide more definitive information on the damage. For more efficient operation and steady supply of electricity, minimizing downtime possibly for maintenance (inspection, repair, and cleaning) is critical. Therefore, short inspection time is of the first priority with respect to the off-line NDE technique.

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The conventional inspection of composite materials relies on water-coupled ultrasonic techniques. These techniques have been extremely powerful as these provide the most straightforward defect images which do not requires post interpretation and analysis. However, use of water is undesirable in some cases: for example, in off-shore wind turbines, only available water is sea water; the saline residue on the blade surface is known to have negative effects on blade efficiency and also pumping the sea water up to the blade height (~100 m) requires large mechanical equipment. Alternative to the water-coupled ultrasonic techniques are air-coupled techniques which are free from dealing with water and can provide rapid inspection of the structures. With the emergence of high efficiency air-coupled transducers, the air-coupled ultrasonic techniques are increasingly employed for composite structures. Some reviews of air-coupled ultrasonic measurement in composites are found in [10–12].

Castings and Cawley [13] first reported the feasibility of using the air-coupled generation and detection technique based on 1–3 composite transducers for NDE of damage in plate structures. They examined the sensitivity of S0 and A0 mode Lamb waves to a bottom notch in a thin steel plate. Castings et al. [14] studied inspection of composite plates using A0 mode Lamb waves generated with air-coupled transducers. They performed C-scan and obtained an image of delamination like damage in carbon fiber composite plate. Recently, Kazys et al. [15] and Ramadas et al. [16–18] have investigated extensively the use of guided waves for the detection and inspection of defects in composite plates. Most of these studies are based on the use of Lamb waves except for the work of Barnard et al. [19]. Barnard et al. have shown that the one-side, pitch-catch, and bulk-wave based inspection is feasible if the direct air-borne sound is appropriately shielded. An air-coupled ultrasonic scanning technique similar to the traditional water-coupled C-scan would be very useful for rapid and reliable inspection of detects as this technique would not require post processing and interpretation of signals and images.

This paper develops a one-side, pitch-catch imaging technique using the shear waves focused at the desirable depth in a composite plate. Ray-tracing simulations are performed in order to visualize the focusing behavior of the refracted shear waves in the specimen and to determine experimental parameters. The proposed focused shear wave technique is compared with a Lamb-wave based technique. The images for delamination and debonding defects in a thick laminate composite plate are obtained. The results demonstrate the feasibility of further developing the present technique for specific field applications in wind turbine blades.

2. Specimens and defects

2.1. Single layer GFRP plate

This 6.2 mm thick GFRP plate has thickness-reduction type defects which were created manually with a tool as shown in Fig. 1. This specimen is used to compare the focused shear wave technique and the Lamb wave based technique. One of the defects examined in this paper is approximately circular with a diameter about 35 mm and a depth about 2.7 mm (circled in Fig. 1(a)). Fig. 1(b) shows the defect on back side while the ultrasonic measurement is performed on the front side.

2.2. Sandwich laminate plate

Fig. 2 shows a picture of the sandwich laminate plate specimen. This specimen has a few different types of artificial defects which are prepared for comparing various NDE techniques including the immersion C-scan, focus shear wave technique, tap testing, and the infrared thermography on these defects in the plate. The specimen is a sandwich laminate plate constructed in three layers: the top and bottom skin layers are made of GFRP (glass fiber reinforced polymer, DB830, Owens Corning) and the core is made of balsa (Baltek SB100 CKAL 5/8″, 3A Composites) in Section C, CFRP (carbon fiber reinforced polymer, PX35UD0600, Zoltek) in Section B, or PVC (polyvinyl chloride, AIREX C70.55 Ck, 3A Composites) foam in Section A. The thickness of the top and bottom layers is 6.2 mm and that of the middle layer is 15 mm. The thickness and surface condition are not uniform but vary section by section. In addition, waviness is visible on all specimen surfaces but each has different degree of undulations. This is expected to affect the imaging performance of the focused shear wave technique that this paper proposes.

Delamination defects are only in the top skin GFRP layer at three different depths between plies; these are artificially created by placing a 0.3 mm thick Teflon sheet (ten 0.03 mm films) in a 5 cm × 5 cm square shape before curing. Their locations are marked as (1), (2), and (3) in Fig. 2; their depths are about 5 mm (between 9th and 10th ply), about 3 mm, and about 1 mm, respectively. As shown in the picture of the specimen, the shallowest delamination at (3) is seen (blue) with naked eyes. While the acoustic impedance of Teflon is much different from those of layers, it is still quite different from the air acoustic impedance. For this reason, ultrasonic reflections from these artificial defects are not as strong as that from real delamination and debonding defects. Debonding defects are at three locations (4)-(6) in Fig. 2. The debonding is created at the lower interface between CFRP and GFRP layers as shown in Fig. 3. This research focuses on only one of them, the one in Section B (at (5) in Fig. 2). As can be seen in Fig. 3, the normal penetration depth to the debonding from the skin is about 21 mm. It appears to be challenging to obtain an ultrasonic reflection signal from a defect at this depth in 200 kHz range used in this research.

The properties of the GFRP and CFRP plates are listed in Table 1. The wave speeds of the GFRP plate are measured at 5 MHz using an immersion ultrasonic technique similar to the double-transmission setup [20]. The GFRP plate has the stacking sequence $[0/90/45/\text{-}45]_s$ and thus a quasi isotropy in the x–y plane is assumed. The measured longitudinal and shear wave speeds as a function of propagation angle with respect to the plate normal direction are shown in Fig. 4. As the wave speeds can only be measured in limited ranges of angle, the experimental data are fitted by wave speeds calculated from the theory for wave propagation in anisotropic media [20,21] in order to obtain the wave speeds in the entire range of propagation angle. These are needed for the theoretical calculations of focusing behavior of refracted shear waves as shown in next section. The CFRP plate is a unidirectional composite with fibers aligned in the y-direction (see Fig. 2) and the wave propagations are in the plane of isotropy. Therefore, the wave speeds are constant, which are calculated from constituents' elastic properties provided by the manufacturer.

3. Focused shear waves

This section develops a simple ray tracing model to predict the shear wave field in the sandwich laminate composite plates. The objective is to visualize the wave field in the specimen and rapidly determine a set of optimum experimental parameters without performing an exact analysis of full wave field [13,14,22]. Full wave field analyses are expensive and time-consuming. Experimental parameters include the life-off distance, the transmission/reception angle, and the distance between the transmitter and receiver as shown in Fig. 5. Under an optimum condition, the refracted