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Investitation of mobile ultrasonic propagation imager as a tool for composite wind blade quality control

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ABSTRACT

According to the statistical reports, almost 50% of wind blade failures are due to manufacturing defects. Therefore, reliable nondestructive testing (NDT) methods are required to create a standard for blade manufacturing quality control that reduces maintenance costs and catastrophic accidents. Applying conventional NDT methods is currently impossible without major modifications; this would also be time-consuming because wind turbine blades are large, thick and heterogeneous composite structures.

This study proposes an in-process quality control (IPQC) method based on an ultrasonic propagation imaging (UPI) system. The UPI system is based on laser-induced ultrasound and has the capabilities of noncontact, fast, curved structural and real-time inspection results. These capacities have the potential to be applied to IPQC in blade manufacturing and assembly in a Smart Blade Factory. To provide a proof-of-concept for Smart Blade Factory based on the UPI system as an IPQC tool, a 750-kW actual blade section was tested, and the inspection results were presented based on a multiple-defect visualization platform. Debonding, inclusion and void defects in a wind blade made of glass fiber reinforced plastic and PVC grid panels were studied. The inspection results proved high feasibility for the application of the UPI system to IPQC in blade manufacturing.

1. Introduction

The environmental concerns and limitations of greenhouse gas emissions have led to increasing interest in renewable energy. According to the Society's Cost of Electricity (SCoE) concept [1] of an electricity cost calculation that includes the broad scope, wind energy is the cheapest of all various energy sources. To supply cheap and reliable electricity, many researchers are studying ways to increase the efficiency and lifespans of power generators. Researchers are also developing health monitoring and quality control technologies in order to save on maintenance and repair costs. According to the statistics in 2010 as shown in Fig. 1, wind turbine blade failures occur because of manufacturing defects (53%) and operating events (47%) [2]. Statistics in 2005 stood at similar values of 51% and 49%, respectively. As part of a structural health monitoring system, some studies have been done for the development of an *in-situ* wireless blade deflection monitoring system [3] to prevent tip deflection tower hits (13% in Fig. 1) and the long-distance laser ultrasonic propagation imaging system [4] to detect blade damages early on e.g. from foreign object impact and lightning. In the manufacturing stage, a strict in-process quality control (IPQC) technology is highly recommended to detect the key manufacturing defects such as adhesive bond failure (19%), voids in skin (17%) and improper curing (17%) as presented in Fig. 1.

Most wind turbine blades are composed of glass or carbon fiber reinforced plastic (FRP) composites and other lightweight materials such as balsa wood or polyvinyl chloride (PVC). Manufacturing defects can include debonding, delamination, voids, improper curing, wrinkling, or matrix cracks. These defects weaken the load bearing capacity of the blade and consequently lead to destruction. As shown in Fig. 2, 43% of composite blade failures are caused from adhesive design and manufacturing errors [2]. Laminate issues also account for 33% of blade failures.

Therefore, most maintenance budgets are allocated to repairing and replacement of the blades. Consequently, the ideal approach to reduce maintenance cost must be to fabricate zero-defect blades because extremely increased cost is required for event detection, damage evaluation and repairing of already installed blades. To achieve this ideal target, industries are requiring advanced IPQC tools that can cover large, thick and curved geometries along with complex material compositions.

Conventional NDT methods are used for quality inspections and include visual inspections, tap tests, ultrasonic tests, thermography

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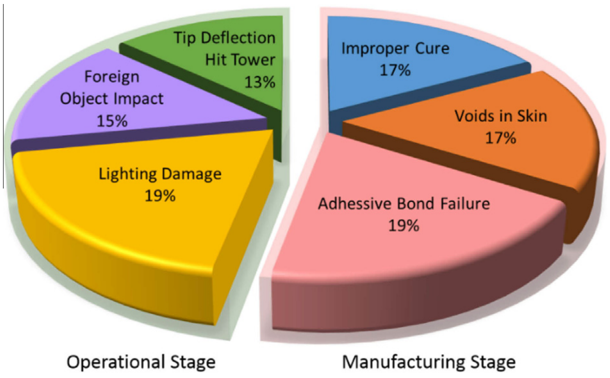

Fig. 1. Blade defect and damage at manufacturing and operational stages [2].

and laser Doppler vibrometers. Although a visual inspection, including a penetrant test, can easily detect surface defects [5], it cannot detect the subsurface defects that are typically found in the blades. Tap tests and ultrasonic tests are useful for all defect types that are generated during the blade manufacturing process, but tap testing systems are not effective on thick blade sections [5]. Ultrasonic inspection systems can easily get the results with defect size evaluation, but a scan gantry is necessary for full-scale blade scanning [6,7].

Thermography utilizes an infrared ray on the structure and has demonstrated good performance for both quality inspections and on-site damage inspections [8]. However, this method has difficulties in evaluating the adhesive condition [9], exhibits slow inspection speeds and suffers from errors during heat loss [8], particularly in thick structures. A scanning laser Doppler vibrometer scans the structure and provides results in an image form. However, this system suffers from low sensitivity and reliability in terms of defect evaluation [10].

Conventional NDT methods are not ideally suited as an IPQC system because the system requires thorough defect detection performance and fast inspection speeds during the manufacturing process. Therefore, many advanced institutes are trying to develop reliable and fast NDE methods for the huge wind blade structures [11,12]. Fig. 3 shows the wind blade NDT systems being developed, such as waterjet ACT C-scanner developed by FORCE Technology and thermal imagery system developed by Fraunhofer institute.

This study proposes an IPQC method based on an ultrasonic propagation imaging (UPI) system [4]. UPI systems offer good potential for IPQC, including fast inspection speeds, real-time inspection result checks and reliable results. Laser scanning using a UPI system is subsequently performed on a blade to verify the failure detection performance of the UPI system. The specimen is a part of a 750-kW wind turbine blade made of glass fiber reinforced plastic (GFRP) with a polyvinyl chloride (PVC) grid panel and an epoxy adhesive. Three artificial debondings are introduced on load-bearing portions on the blade: the leading edge, the trailing edge and the skin-spar bonding section. A multiple defect visualization platform integrated into the UPI system provides instantaneous inspection results with exclusive defect visibility.

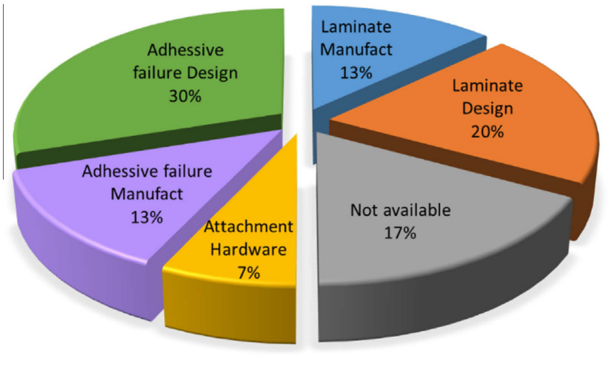

Fig. 2. Composite wind turbine blade failure modes [2].

2. Target structure

Fig. 4(a) shows the airfoil section of a blade that consists of an upper skin, a lower skin and two spars. This specimen is a portion of a 750-kW full-scale blade made of GFRP with a PVC core and an epoxy adhesive. Three artificial debondings were placed in the following bonded areas: the leading edge, the trailing edge and the skin-spar bonding surface, as these are load bearing parts.

On the leading edge, a 15 × 20 mm^2 debonding is located on the curved GFRP surface between the upper and lower skin bonding areas and is shown in Fig. 5. A section of the PVC grid core panel was also included in the 100 × 100 mm^2 scanning area, and the ultrasonic sensor was attached onto the lower skin surface.

On the trailing edge, a 20 × 20 mm^2 square-shaped debonding was placed between the upper and lower skin. As shown in Fig. 6, the scanning area was flatter than on the leading edge, and an ultrasonic sensor was attached to the lower skin surface.

Fig. 7 shows the skin-spar bonding area in detail. The bonding section was almost 50 mm thick and was comprised of 15 mm of GFRP skin, 5 mm of an artificial debonding adhesive layer, 26 mm of an epoxy adhesive layer and 4 mm of spar flange. A 20 × 20 mm^2 square-shaped debonding area and unintentional natural defects were included in the scanning area. The natural defects were an inclusion of ø 3 mm and two surface voids that are ø 1 mm and ø 2 mm in size. The ultrasonic sensor was attached onto the spar flange as shown in Fig. 7(b).

3. Ultrasonic propagation imaging system

The UPI system was composed of three components that processed laser scanning, signal sensing and system control. As shown in Fig. 8, the laser scanning component consisted of a 532-nm Q-switched laser (QL), a QL controller, a laser mirror scanner (LMS), an LMS controller and a beam expender. High-speed laser scanning and non-contact ultrasound generation were based on QL and LMS speeds of up to 20 kHz pulse repetitions. The LMS was equipped with two orthogonal galvano-motorized mirrors at a wavelength of 532 nm. The two orthogonal mirrors were used to control laser pulse beams at each two dimensional scanning point by synchronizing with laser pulse repetitions, thus enabling a scan of the curved surface [4]. A beam expender supported the long-distance inspection (more than 10 m) between the UPI system and the scanning area.

The signal sensing component was comprised of an ultrasonic sensor and a sensor system. A commercial ultrasonic sensor that was either contact or noncontact could be used for this purpose. For this study, an amplifier-integrated broadband PZT sensor was used to receive the signals. The ultrasonic signals were filtered and amplified by the sensor system.

The system control component utilized a computer that controlled all parts of the UPI system in synchronization while detecting and saving the ultrasonic signals. The system also provided the inspection results with a multiple-defect visualization method in real time due to its fast signal processing board.

The UPI system inspected the specimen via laser scanning as shown in Fig. 9. Fig. 10 shows a design and schematic of the Smart Blade Factory equipped with UPI systems. The UPI system is easily applied to the inspection of the bonding conditions on