Renewable Energy 99 (2016) 170–179

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

An experimental study of acoustic emission methodology for in service condition monitoring of wind turbine blades

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
17 June 2016
Accepted 19 June 2016

Keywords:
Acoustic emission
Fatigue
Structural health monitoring
Wind turbines blade
Composite materials

ABSTRACT

A laboratory study is reported regarding fatigue damage growth monitoring in a complete 45.7 m long wind turbine blade typically designed for a 2 MW generator. The main purpose of this study was to investigate the feasibility of in-service monitoring of the structural health of blades by acoustic emission (AE). Cyclic loading by compact resonant masses was performed to accurately simulate in-service load conditions and 187 kcs of fatigue were performed over periods which totalled 21 days, during which AE monitoring was performed with a 4 sensor array. Before the final 8 days of fatigue testing a simulated rectangular defect of dimensions 1 m × 0.05 m × 0.01 m was introduced into the blade material. The growth of fatigue damage from this source defect was successfully detected from AE monitoring. The AE signals were correlated with the growth of delamination up to 0.3 m in length and channel cracking in the final two days of fatigue testing. A high detection threshold of 40 dB was employed to suppress AE noise generated by the fatigue loading, which was a realistic simulation of the noise that would be generated in service from wind impact and acoustic coupling to the tower and nacelle. In order to decrease the probability of false alarm, a threshold of 45 dB was selected for further data processing. The crack propagation related AE signals discovered by counting only received pulse signals (bursts) from 4 sensors whose arrival times lay within the maximum variation of travel times from the damage source to the different sensors in the array. Analysis of the relative arrival times at the sensors by triangulation method successfully determined the location of damage growth, which was confirmed by photographic evidence. In view of the small scale of the damage growth relative to the blade size that was successfully detected, the developed AE monitoring methodology shows excellent promise as an in-service blade integrity monitoring technique capable of providing early warnings of developing damage before it becomes too expensive to repair.

1. Introduction

Wind energy is recognized as a reliable and affordable source of electricity in many countries. According to the Global Wind Report, by the end of 2014, the global wind energy capacity has reached 369.6 GW [1]. The wind turbine technology has advantages amongst other applications of renewable energy technologies due to its technological maturity, good infrastructure and relative cost competitiveness [2]. Success of a wind energy project relies on the reliability of a wind turbine system. Poor reliability will directly result in the increase operation and maintenance (O&M) cost and the decrease of the wind turbine system lifetime. To improve the wind turbine system reliability, it is important to identify critical components and characterize failure modes, this will allow the maintenance staff direct their monitoring, and focus on monitoring methods.

Wind turbines can suffer from moisture absorption, thermal stress, wind gusts and sometimes lightning strikes. Damage can occur at any part of the wind turbine, gear box bearings, generator bearing, wind turbines blades, a bolt shears, and a load-bearing brace buckles etc. [3]. As the blades are the key elements of a wind turbine system and the cost of the blades can account for 15–20% of the total cost, extensive attention has been given to the condition monitoring of blades [4]. Wind turbine blades' most

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http://dx.doi.org/10.1016/j.renene.2016.06.048
0960-1481/© 2016 Published by Elsevier Ltd.

common used materials are carbon and glass fibre materials (GRP) [5,6]. They can be damaged by rain, extreme wind, lightning, bird strikes, and UV rays [7]. Besides they are subject to the cyclic stress loading because they transfer the mechanical flow from the wind to the flow of up to several MW electricity powers. In service failure is thus a significant risk and can have catastrophic consequences, with detached blades able to fly free for up to a mile and high collateral damage to the tower and nacelle caused by out of balance torques [8]. It is usually difficult to predict the remained life time of a blade, but it is possible to determine the condition of the blade and warn of failure.

The application of condition monitoring has grown considerably in the last decade due to its ability to allow real time monitoring of assets as a means to achieve the goal of early failure detection [9]. The condition monitoring techniques for wind turbine blade include strain measurements, ultrasonic testing and AE. For the wind-farm operator, using strain gages to record the load history in the wind turbine blade has the advantage of understanding loads caused by the damage which enables a better detection of potentially damaging situations. However, the operational conditions lead to a lack of robustness for the use of strain gages and this technique has not been widely used for condition monitoring. The application of fibre bragg grating (FBG) showed technical advantages over the conventional strain sensor [10] and it can be expected to become an important tool for condition monitoring in the near future. Ultrasonic testing for wind turbine has become an important tool due to its capability to provide information about the state of the composite materials beneath the surface such as exposing the dry glass fibre existence or delamination [11]. For this method, a high degree of operator skill and integrity is required, and the spurious indication could mislead unnecessary repairs.

Acoustic emission (AE) is elastic wave generated by a material when it undergoes inelastic strain or rupture. The crack initiation and propagation of cracks in composite has been successfully detected using AE [12–14]. One of the advantages of AE technique for wind turbine blade inspection is that it is a passive technique requiring no power input to the sensors. The sensors can be lightweight and readily embedded in a new blade or retrofitted to existing blades without any intrusive effects [15,16]. This of course offers the advantage of being applied into a condition monitoring system. However, a significant drawback of AE technique for crack growth monitoring in many applications is that there are many sources of AE other than the crack of interest. These sources thus constitute noise which can be both random and coherent, sometimes exceeding by far the crack signals. Such noise has been observed in operational conditions for wind turbine blades [17]. The steady wind impact will generate standing waves which will be largely time coherent but variable with the wind speeds; particularly gusts will generate time random components in the standing waves.

AE monitoring has been investigated on small-scale wind turbine blade tests under laboratory conditions. Joosse, P. A. et al., and Dutton, A. G. et al., [18,19] showed it is able to detect the damage zones by the cumulative AE evens curve by a couple of sensors which locate along a 4.5 m long blade. The primary detecting method is based on Kaizer and Felicity Effect. Data were acquired during static tests and low frequency fatigue tests controlled under laboratory conditions, which lowered the difficulty of AE signal processing. Zhou, Bo et al. identified the fatigue cracks in a 3 m long blade by using the fractal dimension (FD) analytical method [20]. This method quantitatively describes the non-linear fault features for identification and predicting the complex non-linear dynamic characteristics of AE signals. The complexity variations are linked with the energy changes in the AE signal by means of FD, providing a fast computational tool that tracks the existence of a crack. Niezrecki, Christopher, et al., focused on a 9 m long blade fatigue testing, AE data was only recorded only when the loaded blade was in the top and bottom 10% of the peak deflection due to the flaw growth in a fatigue test occurs primarily near the maximum stress analysis. AE location calculations were conducted in real time, the AE events are defined as the arrival of a wave at three or more sensors within a time window which is calculated based on the wave velocity in the blade [21]. The results showed the located events near the crack correspond to a significant energy release. However, the wind turbine blades in operation experience various forms of loads and impact events, which can cause damage in any area at any time. Besides, wind turbines have more than quadrupled in size. The blade length today can be over 50 m. It is necessary to carry out the AE monitoring on a large wind turbine blade under a more complex, close to real in operation condition.

In this paper, a new technique for detecting AE crack growth signals from wind turbine blades in the presence of accurate simulation of the noise to be expected from the blade when in service is described. A fatigue damage growth monitoring test totalled 21 days in a complete 45.7 m long wind turbine blade was carried out, during which AE monitoring was applied continuously with a 4 sensor array. Before the final 8 days of fatigue testing a simulated rectangular defect of dimensions 1 m $\times$ 0.05 m $\times$ 0.01 m was introduced into the blade. The growth of delamination up to 0.3 m in length and channel cracking from this source was successfully detected from AE monitoring. By using the triangulation method, 29 AE event locations computed by triangulation are clustered around the induced defect providing evidence of the growth of damage originating from this source.

2. Experimental rig

2.1. Wind turbine blade support

The blade being tested was a glass-reinforced plastic composite blade, measuring circa 45.7 m in length, with 2 internal supporting webs running the entire length of the blade. An external view of the entire blade length is shown in Fig. 1, prior to the tests. The blade was installed on the test stand with the suction side of the blade facing the test lab floor as shown in Fig. 1 (b).

2.2. Cyclic fatigue loading

Multiple pairs of Compact Resonant Masses (CRMs) were used to excite vibrations in the blade, which served both to produce the conditions under which crack defects generate AE and to simulate the natural vibrations that the blade would experience when in service. These masses were supported on steel saddles at initial distances of 30 m and 35 m measured from the root of the blade, as shown in Fig. 2. The saddles clamp the blade using wooden profiles cut to the shape of the blade using CAD data. The stroke and frequency of the moving mass of the CRMs could be adjusted during the course of the experiment to suit specific root bending moments. A MOOG Hydraulic Test Controller and bespoke software was used to apply a sinusoidal excitation profile which was operated at the first resonant mode of the blade, such that the hydraulic power consumed by the actuators is almost entirely coupled into the blade. A combination of actuator position and mass, and strain ranges were used in the control of the test.

2.3. Acoustic emission monitoring set up

AE signals generated during the test were recorded and analysed using a data acquisition system developed by TWI [22]. This system is based on the National Instruments PXIe-1071 card