The review of non-destructive testing techniques suitable for inspection of the wind turbine blades

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Abstract

Wind power is a promising source of environmentally safe and renewable energy with a high potential. However, in order to fully exploit energy of wind power the construction elements of the wind turbine should be inspected periodically. Wind turbine blades are complicated objects for inspection because they have an arbitrary curved surface, are multi-layered, have variable thickness and are made from anisotropic materials.

The presented study covers an overview of the techniques which are used or could be used for on site condition monitoring and effective NDT of wind turbine blades. Inspection methods based on vibration analysis, thermography, X-ray imaging, acoustic emission and ultrasound are reviewed. The objective of this study is review of different NDT techniques, which are used, or could be used for non-destructive testing of wind turbine blades, taking into account the complicated structure of the wind turbine blades as well as possibility to make non-destructive testing in harsh on-site conditions.

Keywords: wind turbine blade, multi-layered materials, NDT techniques, ultrasonic

Introduction

Wind power is a promising source of environmentally safe and renewable energy with a high potential. Reliability of wind turbine is critical in order to extract maximum amount of energy from the wind. As wind turbines are becoming larger and are placed at more remote locations (like offshore), a reliable monitoring of the health condition of the wind turbines becomes more important. However, in order to fully exploit the energy of wind power (to prevent the damages and accidents of the construction components) the construction components of the wind turbine should be inspected and improved periodically.

It is necessary to perform continuous condition monitoring of wind turbine blades, in order to estimate level of critical damage at an initial stage before collapsing and to perform detailed inspection with elimination of the broken-down components. One of the essential components in wind turbines are their blades. Blade failure is very costly because it can damage other blades, the wind turbine itself, and other wind turbines located in neighbour. The efficient NDT procedures should extend wind turbine life and reduce failure possibility [1].

There are developed different techniques and algorithms, which enable to monitor the performance of wind turbine as well as an early fault detection to keep away the wind turbines from catastrophic conditions due to sudden breakdowns. To keep the wind turbine in operation, implementation of condition monitoring system becomes very important. Inspection methods based on ultrasound, radiography, thermography, and acoustic emission are widely applied, they enable to perform quality control and also on site inspection of the components [2].

Once the design of a wind turbine blade has been completed and the turbine has been built, it is necessary to perform the quality control in order to avoid manufacturing non-regularities and deviations from the design. The full-scale testing of the constructed wind turbine is performed in a laboratory and on an operating wind turbine in a field environment [3, 4]. Wind turbine blades, while in operation, encounter very complex loading sequences, due to the stochastic nature of wind conditions on wind turbines sites. The suitability of a particular blade to operate under such conditions is assessed through a certification procedure, which covers series of static and fatigue laboratory tests on the blade. The purpose of such tests is to ascertain that the blade can survive the applied (static and fatigue) loads [5].

Fibre-reinforced composites are used in many fatigue-critical applications, like construction elements of wind turbine blades. Due to their heterogeneous and anisotropic nature, their fatigue behaviour is rather complex and several damage mechanisms can develop during fatigue life. A damage mechanics-based fatigue model for fibre-reinforced plastics has been created, where both stiffness degradation and (possible) accumulation of permanent strain were simulated from the first loading cycle up till final failure. Finite element simulations have been used in order to predict the damage growth rate [6].

A full-scale static structural test was also carried out at the simulated aerodynamic loads of turbine blade. The experimental results showed that the designed blade had structural integrity. The predicted mass, spanwise centre of gravity, blade tip deflection and first flap - natural frequency agreed well with the corresponding measured values within 4% error. Furthermore, the measured strain results had a good agreement with the analytical results [7].

A global non-linear finite element model of the entire blade was prepared and the boundaries to a more detailed sub-model were extracted. Such model was calibrated by full-scale test measurements. Local displacement measurements helped to identify the location of failure initiation which leads to catastrophic failure [8].

The objective of this study is review of different NDT techniques, which are used, or could be used for non-destructive testing of wind turbine blades, taking into account the complicated structure of the wind turbine blades as well as possibility to make non-destructive testing in harsh on-site conditions.

The object of investigations

Wind turbine blades are complicated objects for inspection by non-destructive techniques: they are multi-layered, have a variable thickness, have an arbitrary curved surface (Fig. 1, a), are made from anisotropic materials and have a lot of manufacturing non-homogeneities. The view of the wind turbine blade cross-section, made mainly from the GFRP (glass fiber reinforced plastic) composite layers joined together by epoxy glue, is presented in Fig.1, b.

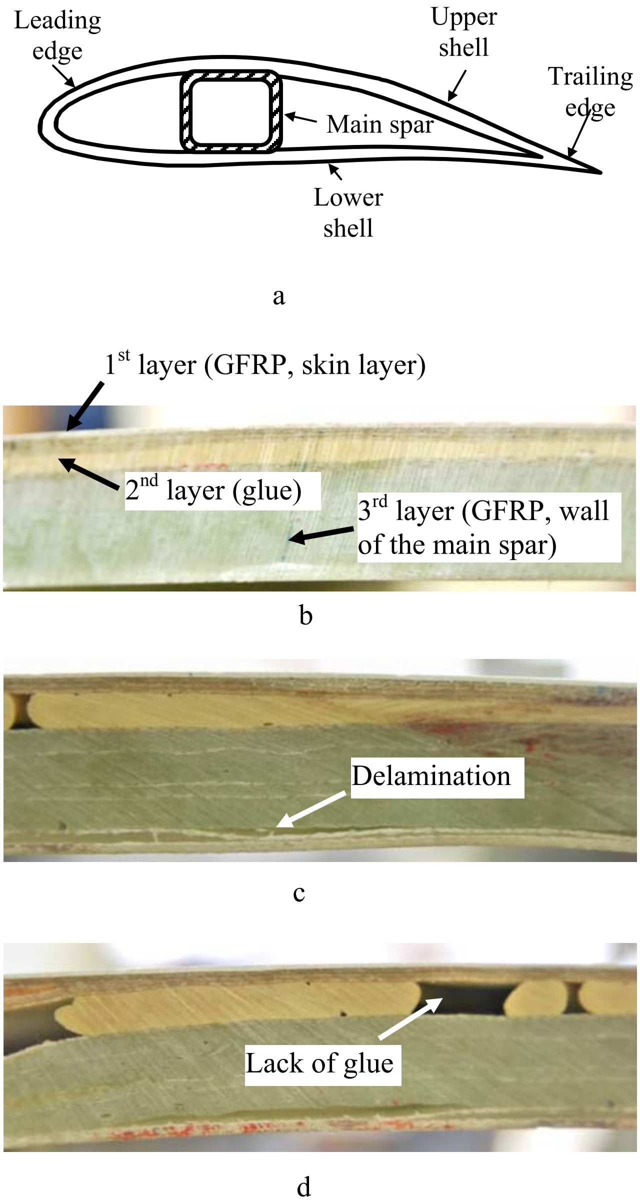

Fig.1. **The views of the wind turbine blade cross-sections: a - typical cross section, b – main spar cross- section without defects, c – main spar cross- section with delamination, d- main spar cross- section with lack of epoxy glue**

The cross-sections show the multi-layered structure of the wind turbine blade: the outer skin layer is made of GFRP with dye coating, the 2nd layer is epoxy glue and the 3rd layer is made of GFRP. During manufacturing of the wind turbine blades the internal non-homogeneities between individual layers appear like delaminations between the GFRP layers (Fig.1, b), lack of epoxy glue (Fig.1, c) and etc.

Different NDT techniques, suitable for testing of wind turbine blades

Field of NDT offers different techniques which are used or could be used for the inspection of wind turbines such as vibration analysis, thermography, X-ray imaging, acoustic emission and ultrasonic testing.

Vibration analysis is the most known technology applied for condition monitoring, especially for rotating equipment. The types of sensors used depend more or less on the frequency range (0.01..100 kHz), relevant for the monitoring: the position transducers use the low-frequency range, velocity sensors use the middle frequency, in accelerometers the high-frequency is used and spectral emitted energy sensors use very high frequencies (acoustic vibrations). Monitoring of the physical conditions of materials is mainly focused on crack detection and growth. Commonly used methods are normally off-line and not suitable for on-line condition monitoring of wind turbines. Exception might be the usage of optical fuses in the blades and acoustic monitoring of structures. For condition monitoring the strain gauges can be applied, however they are not robust during a long term use. The strain measurements can be very useful for lifetime prediction and safeguarding of the stress level, especially for the blades. For that purpose the optical fibre sensors are promising, however they are still too expensive [9].

Thermography is often applied for monitoring and failure identification of electronic and electric components. Typical thermographic applications involve the introduction of a controlled thermal load on the object of interest. Variations in the thermodynamic properties of the object then produce surface temperature patterns which can be detected with an infrared imaging system. Hot spots, due to degeneration of components or bad internal contact can be identified in a simple and fast manner. This method is particularly sensitive to flaws near the inspected surface [9, 10].

X-ray imaging relies on the different levels of absorption of X-ray photons as they pass through a material. Such systems are sensitive enough to detect change of at least 1-2% of the material thickness or density. In order to detect tight delaminations, having gaps less than 50 μm in width, the backscatter X-ray imaging technique can be used. The X-ray backscatter data contains quantitative information about variations in density, which is caused by changes in material properties or internal delaminations. Using this technique it is possible to locate the internal non-homogeneities within the depth of the material. The advantage of X-ray inspection is the extremely good contrast sensitivity, as a result variations of density less than 0.1 % are detectable in the true three-dimensional perspective [10].

In acoustic emission technique elastic waves are used, which are generated by the rapid release of energy from localized sources within a multi-layered structure of the blade. Acoustic emission technique is suitable for detecting the possible failure of blades in the real time and during their testing in laboratory environment. Weak points in the construction design are identified [9, 11-13]. Acoustic monitoring has a strong relationship with vibration monitoring. However there is also a principal difference. While vibration sensors are rigidly mounted on the component involved and register the local motion, the acoustic sensors perform registration of the component response. They are attached to the component by a flexible glue with a low attenuation. These sensors are successfully applied for monitoring of bearing and gearboxes. There are two types of acoustic condition monitoring: passive type - when the excitation is performed by the component itself and active type - when the excitation is externally applied [9]. In the case of acoustic emission application for the testing of a fiberglass structure, the source of emission is cracking of matrix and fibers. The internal crack inside the fiberglass structure will involve all these mechanisms. Which of the emission generation mechanisms is dominating will depend upon the material characteristics and the locally applied stress field in every region of the material. The presence of acoustic emission in a fiberglass structure subjected to an external load indicates a local failure in some part of the structure. However, during the initial loading or at loads low compared with the normal load, fiberglass structure generates some acoustic emission by itself. In emission informative signals from internal cracks and non-homogeneities are present; however such effect can be used for localisation of the regions having high residual stresses. In a large fiberglass structure, the optimum use of acoustic emission involves spatial location of the acoustic emission sources. However, the main problem with the localization of an acoustic source in fiberglass having complex structure is very high acoustic attenuation and phase velocity dispersion. Due to the high attenuation, a two dimensional source location set-up covering the entire surface of a wind turbine blade could require the essential number of sensors [9, 11-13].

Ultrasonic techniques for NDT of wind turbine blades

The propagation characteristics of ultrasonic waves are used to determine material properties throughout the volume of a turbine blade. This technique is especially useful for detection and characterization of surface and subsurface flaws [11-13]. The ultrasonic C-scan imaging can be used for the area mapping of the composite delamination or interface disbond. Three different techniques can be used for this investigation: pulse-echo, through transmission and pitch-catch. However, the influence of overlapped reflections, scattering and attenuation of the reflected ultrasonic waves from the multi-layered structure appears. The scattering effect also has a negative impact to the propagating ultrasonic waves and requires to use lower frequencies [11].

When the thickness of the thin layers of the multi-layered structure of the wind turbine blade (especially of the front skin layer) has to be measured, the delay line between surface of the transducer and the outer surface of the test object could be used. The principle of the pulse echo technique combined with a delay-line is presented in Fig. 2. For acoustic contact between the delay line and surface of the test object, the coupling liquid, for example low viscosity oil, gel or water could be used. The delay line helps to reduce influence of the transducer's own reverberations to the elongated reflections from the internal structure of the wind turbine blade. In this case, the signals reflected by internal interfaces or non-homogeneities in the object may be exploited to measure and, consequently, to characterize the internal multi-layered structure of the wind turbine blade. This technique is suitable for a quality control and for estimation of the adhesion level between individual layers, for example, delamination between the front skin layer and the epoxy glue [14].

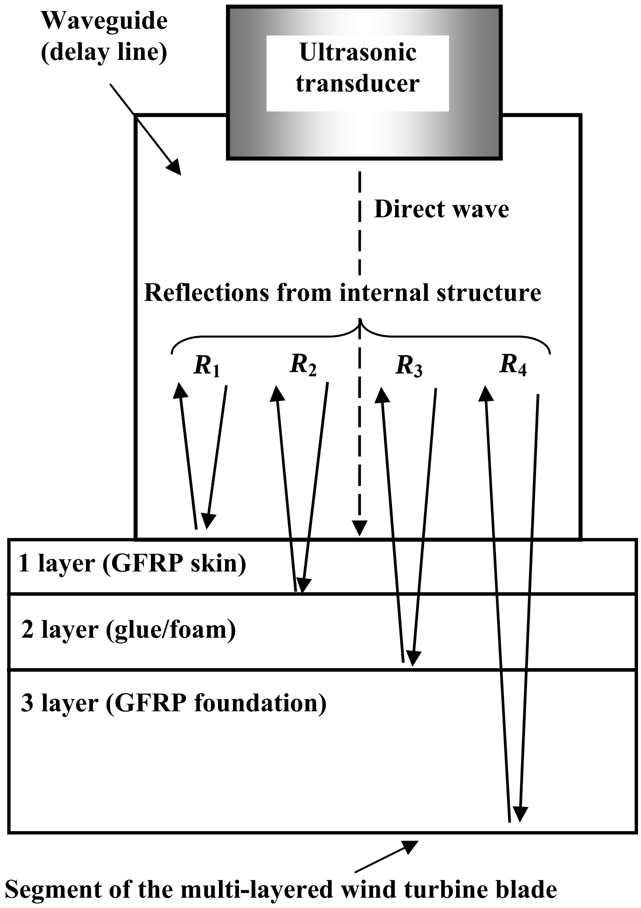

Fig.2. **The principle of the pulse-echo technique for investigation of wind turbine blade**

Another ultrasonic technique, which could be suitable for testing of wind turbine blades, is based on exploitation of ultrasonic guided waves. Application of the ultrasonic guided waves allows estimation of location and type of the internal defects. In the case of guided wave's interaction with structural discontinuities, the guided waves scattering in all directions as well as mode conversion occurs. The different transducer techniques for generation and reception of guided waves, including both conventional and non-conventional piezoelectric transducers are proposed in [15]. There are two approaches commonly used in the structure health monitoring using guided waves: pulse–echo and pitch–catch.

The principle of the air-coupled guided wave technique (pitch-catch) is presented in Fig. 3 [16]. The results obtained using this technique show, that it is a reliable technique, which enables to find defects in wind turbine blades [16]. Using this technique it is possible to inspect the internal structure of the whole multi-layered structure of the wind turbine blade and to find delaminations, lack of glue, etc. [16].

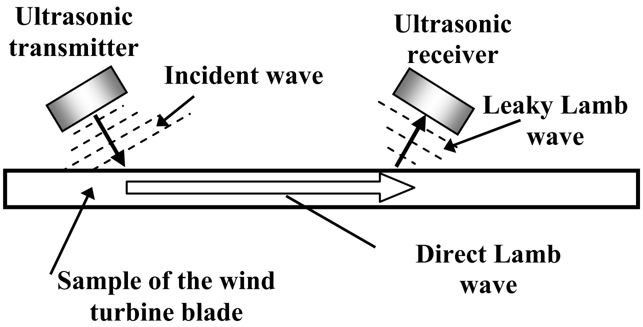

Fig.3. **The principle of the air-coupled guided waves technique for investigation of wind turbine blade**

From various characteristics of the received ultrasonic signal, such as the time of flight, amplitude, frequency content, etc., the information about the damage of wind turbine blade can be obtained. In order to estimate the type of an internal defect, the signal-processing algorithms should be applied. The application of the time-frequency techniques, like the Wigner-Ville distribution, the Hilbert-Huang transform and also Wavelet transform can be used in order to extract more information about internal defects [15, 17-19].

In order to enhance the damage-detection capability of wind turbine blades the more sophisticated processing techniques, like a continuous wavelet transform-based approach could be applied [17 - 19].

Conclusions

In this study an overview of the techniques for effective NDT and on site condition monitoring of wind turbine blades is presented. Inspection methods based on vibration analysis, thermography, X-ray imaging, acoustic emission and ultrasound are reviewed. The analysis of the different NDT methods had shown that now there is no optimal technique available. Different techniques can show different material properties and different defects.

Ultrasonic non-destructive testing techniques are most promising. The two ultrasonic techniques have been analysed in more detail. The first one is based on pulse-echo mode using the ultrasonic transducer with a delay line. Using this ultrasonic technique it is possible to inspect the adhesion level between the thin front-surface and the subsurface layers. Another ultrasonic technique is based on application of the low frequency air-coupled guided waves. This technique does not require any coupling liquid between ultrasonic transducers ant surface of the test sample. Using this technique it is possible to inspect a quality of the bonding between all layers of the multi-layered structure of the wind turbine blade in a region between transmitting and receiving transducers.

For non-destructive testing of wind turbine blades it would be best to use several techniques in order to find different types of defects in different places of wind turbine blade.

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Neardomųjų bandymų metodų vėjo jėgainių mentims tirti apžvalga

Reziumė

Vėjo energija yra vienas iš perspektyvių atsinaujinančių energijos šaltinių. Tačiau kad vėjo energija būtų naudojama saugiai, vėjo jėgainės konstrukciniai elementai turi būti periodiškai tikrinami. Vėjo jėgainių mentės yra sudėtingas tikrinti objektas – jos yra kreivo paviršiaus, įvairaus storio, daugiasluoksnės, pagamintos iš anizotropinių medžiagų.

Straipsnyje apžvelgiamos vėjo jėgainių būsenos stebėsenai ir neardomajai kontrolei atlikti dabar naudojamos technologijos arba tos, kurios galėtų būti naudojamos. Tai rentgeno, termografiniai, akustinės emisijos ir ultragarsiniai metodai. Plačiau apžvelgti – ultragarsiniai. Kai yra prieiga tik iš vienos objekto pusės, gali būti naudojamos dvi ultragarsinės technologijos: nekontaktinis (per oro tarpą) ultragarsinis matavimo naudojant nukreiptąsias Lembo bangas metodas ir ultragarsinis impulso atspindžio, gaunamo naudojant ultragarsinį keitiklį su suvėlinimo linija, metodas.

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