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Journal Paper

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- Renewable Energy-

2020

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Cite as Márquez, Fausto Pedro García; CHACÓN, Ana María Peco. A review of non-destructive testing on wind turbines blades. Renewable Energy, 2020.

D.O.I : https://doi.org/10.1016/j.renene.2020.07.145

A Review of Non-Destructive Testing on Wind Turbines Blades

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Received: date; Accepted: date; Published: date

Abstract: Wind energy, with an exponential growth in the last years, is nowadays one of the most important renewable energy sources. Modern wind turbines are bigger and complex to produce more energy. This industry requires to reduce its operating and maintenance costs and to increase its reliability, safety, maintainability and availability. Condition monitoring systems are beginning to be employed for this purpose. They must be reliable and cost-effective to reduce the long periods of downtimes and high maintenance costs, and to avoid catastrophic scenarios caused by undetected failures. This paper presents a survey about the most important and updated condition monitoring techniques based on non-destructive testing and methods applied to wind turbine blades. In addition, it analyses the future trends and challenges of structural health monitoring systems in wind turbine blades.

Keywords: wind energy; wind turbine blade; condition monitoring system; non-destructive testing; structural health monitoring

1. Introduction

The European Commission has set as priority to promote the growth of the wind energy industry as part of the plan for decarbonization in Europe in the coming decades (Decision Nº 646/2000/EC of the European Parliament and of the Council of February 28, 2000 [1]). This caused a rise in wind energy use in the last years [2].

The total accumulated energy produced by wind turbines (WTs) has increased 11% in 2017, being the total investment of 107 b$ by that year [3]. This industry requires to increase the reliability, availability, maintainability and safety (RAMS) of the WTs [4].

It has been demonstrated that 15-35% of the total cost are related to operation and maintenance (O&M) costs in offshore WTs [5], being 80% invested in unplanned failures. Therefore, it is important to prevent failures in WTs, where condition monitoring systems (CMS) are being employed on that [6]. CMS are based in a set of sensors and electronic devices to read the signals, together with an approach to study the state of the component.

Igba et al. [7] justified the need of CMS of through-life engineering service (TES) for WT. The authors indicated that there are new research works, e.g. autonomous maintenance, to improve maintenance techniques applied to WT gearboxes. According to Junior et al. [8], the failures of offshore WT gearboxes appear in the first year of their life cycle.

Many high sampling rate sensors are being used for electrical components, generating a large amount of data. There are new researches about novel methods and algorithms applied on that [9-11]. For example, Wang et al. [12] developed algorithms that work with a reduced number of data and failures with a good accuracy. Romero et al. [13] demonstrated the need to improve the data processing due to the false alarms (the importance of false alarms in WT was presented by Marugán et al. in [14,15]), or other faults that are overlooked. The authors defined the normal operating limits for each WT according to the vibration signals. Finally, they merged CMS data (vibrations) with supervisory control and data acquisition (SCADA) parameters, mainly power and wind velocity, with good accuracy [16,17].

The size of the WT blades (WTBs) has increased in recent years, leading to greater efficiency and energy production, but presenting higher failure probability [18,19]. Non-destructive testing (NDT) techniques have been developed and applied recently to WTBs [20,21]. NDT does not modify the physical, chemical, mechanical or dimensional properties of the WTB. This paper presents and general overview of the main NDT techniques used for WTBs, with a recent survey of the most recent research paper on each topic.

2. Non-Destructive Testing in Wind Turbine Blades

Marti-Puig et al. [22] found that approximately €2.2 billion are employed to repair WT failures, where an important amount is done on WTBs. There are numerous research studies based on NDT in WTBs [23,24]. NDTs can detect both surface and internal faults in WTBs, leading to improved quality, safety and failures prevention. The NDT are applied in structural health monitoring (SHM) systems for fault detection and diagnosis (FDD) [25-27]. According to Muñoz and García [27], the NDT techniques can reduce corrective and preventive maintenance tasks, and to avoid critical failures in WTBs, leading to extend the life cycle of the structure. Rubert et al. [28] analysed the levelized cost of energy (LCOE) of the WT, where NDT helped to reduce it.

WTB fatigue reduces its life cycle, and Abraham et al. [29] stated that "the technological means to measure fatigue in civil structures are obsolete, imprecise and inappropriate". For this reason, the Innovation and Networking for Fatigue and Reliability Analysis of Structures- Training for Assessment of Risk (INFRASTAR) project is working on optimising the design of new structures, as well as improving crack dimensioning, the fatigue damage monitoring and predicting WTB service life [30].

WTB are difficult to monitor because of their curved shape, and they are made of fiberglass plastics and other sandwich areas that are made of wood or plastic foam, i.e. they are very complex. In addition, WTBs are composed by different layers with a variable thickness and anisotropic materials. NDT are employed in WTBs during their manufacture and operation. A "post mortem" study of a WTB was carried out by Chen [31] to find out the characteristics of macroscopic failure and microscopic fractographic morphologies by means of X-ray computed tomography.

Gholizadeh [32] presented an exhaustive review of NDT methods of composite materials, where they were classified into two main categories: contact and non-contact NDT methods. Figure 1 shows the most common classification of the NDTs in WTB [33].

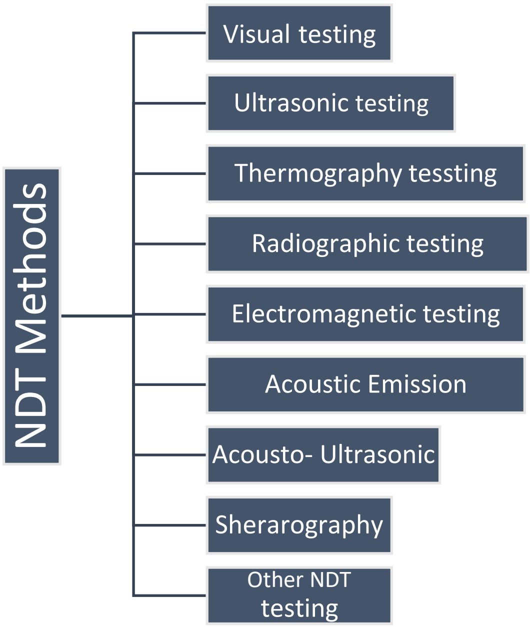

Figure 1. Classification of NDT in WTB.

3. Structural Health Monitoring and WTB

The WTBs are becoming bigger and more complex, and many sensors are being employed for CMS. This data is transmitted to a central monitoring system, where it is analysed. Yang et al. [33] did a survey study of NDT in WTB, analysing its advantages and limitations through comparative studies. Martinez-Luengo et al. [34] carried out a review of the statistical pattern recognition methods for SHM for offshore WTB [35]. They evaluated each stage that SHMS can contribute to the improvement of a condition-based maintenance (CBM) strategy. Optimizing each stage is intended to increase the efficiency of the strategy, reducing maintenance costs by preventing faults.

Yu et al. [36] implemented a deep belief network (DBN) in FDD. DBN employed the signals without knowing the physical model. The simulation results show that the method is robust, although it should be tested on real WTBs.

Cho et al. [37] employed a Kalman filter to fault detection and isolation (FDI). They calculated the angle of the WTB pitch and utilised an isolation algorithm that determines the type, location, magnitude and time of the fault. Finally, a fault-tolerant controller is able to avoid unexpected external loads. Experimental results have demonstrated its effectiveness and the ability to detect and isolate various faults at an early stage.

FDD has been done and automated by Koitz et al. [38]. However, the location of the fault is generally done manually according to the experience of the workers. SHM techniques are being employed to support the workers, considering the life cycle, adverse weather conditions, manufacturing faults, etc. Turnbull and Omenzetter [39,40] employed fuzzy finite element model updating (FFEMU) to analyze the damage of a small-scale WTB. This method was able to accurately predict the magnitude and location of the WTB faults. They also employed a new SHM methodology using two optimization algorithms for fuzzy finite element model, both the severity of the fault and its location were experimentally simulated in the WTB [40].

The analysis of cointegration residues is used for monitoring of the WT in operation and fault detection. Dao et al. [41] designed a quality control chart method based on residual values. The results shown that their method was robust and reliable. Nielsen and Sørensen [42] proposed a method based on a Markov deterioration model to optimize the maintenance of WTs. Data from previous inspections is needed and obtained by means of Bayesian dynamic networks in order to apply this method.

The main techniques presented are focused on advances models based on statistical approaches applied in signal processing and pattern recognition. The current research, therefore, focuses on complex signals and analysing large amount and variety of data. The methods are also being designed and developed to study the condition of the component in real time. There a lot of studies based on artificial intelligence, and it will the trend in the next few years according to the researches trend.

3.1. Visual Testing

Visual inspection is a technique commonly used as a non-destructive testing (NDT) method to find faults in WTB as discontinuities and cracks. WTs are regularly found in isolated and complex environments with difficult access. To reduce maintenance costs and extend the life of the WTB, UAV inspections employ photogrammetric or cameras to provide a visual reconstruction of the WTB. In the future, the use of UAVs will be common for visual testing, as well as the artificial intelligence methods for detecting faults on the WTB surface and prognosis on-line of the SHM of WTBs.

Maintenance tasks are based mainly on visual testing (VT) in WTBs, or visual inspection (VI) (see Figure 2). Stutzmann et al. [43] used a conditional probability model to analyse the inspections with numerical simulations about cracks due to fatigue. They tried to reduce the uncertainty to estimate the useful life of WT structures due to fatigue. VT is also used for welding analysis. However, it depends on the experience of the workers and it is subjective.

Kim el al.[44] proposed a simple and essential NDT for WTBs. The damage detection system is based on pan-tilt zoom camera system. This system is used for the fault location in WTBs. It is able to detect 2 cm width crack to a distance of 200 m.

The variety of faults in WTB and the lack of images of these faults cause that the fault diagnosis to be difficult. Yu et al.[45] proposed a method for fault diagnosis in WTB based on semantic characteristics of faults by a transfer characteristics extractor. It emulates the behaviour of human vision.

Poozesh et al. [46] analysed the performance of conventional 3D digital image correlation (3D DIC) and 3D point tracking (3DPT) approaches, and proposed a multi-camera measurement system for WTB maintenance tasks. Their approaches can inspect large areas of the WTB, where no complex data acquisition systems are required.

Unmanned aerial vehicles (UAVs) are being used to analyse superficial faults on the WTB, e.g. cracks [47]. Khadka et al. [48] employed a digital image correlation (DIC) system embedded in an UAV to study the dynamic characteristics of WTB. This system allows the remote condition monitoring of WTBs, both in offshore and onshore wind farms. Wang and Zhang [49] employed a cascade classifier trained to detect cracks. The method was validated for identifying and locating cracks in WTBs. They utilised a visual test that combine images from UAV together with a photogrammetric payload to perform the visual reconstruction of the WTB and its condition. They employed a photogrammetric software to process the images and to generate a 3D profile of the WTB. It was due by using a waypoint guidance algorithm that captures images at a constant distance from the WTB.

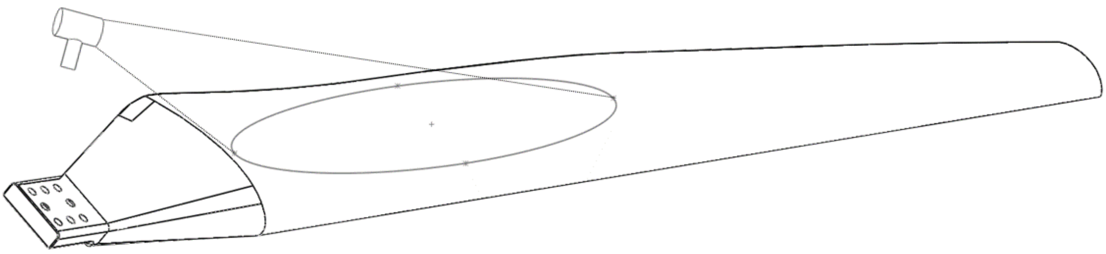

Figure 2. Temperature sensor on the WTBs.

Table 1 shows the main strengths and weaknesses of the methods analysed in this section.

Table 1. Main methods based on visual testing in WTB: Strengths and Weaknesses.

Ref.	Method	Strengths	Weaknesses
[43]	A conditional probability model to analyse results from inspections together with numerical simulations of fatigue cracks	Reduction of uncertainty in the estimation of the remaining life of monopile substructures of WTs, e.g. WTBs	It should need the integration of these results with a decision model for the study of the life cycle of WTs.
[44]	Visual Testing system based on pan-tilt zoom camera system.	It is able to detect 2 cm width crack located at 200 m distance.	This method can only detect external surface damage
[45]	Fault semantic features with transfer feature extractor	High learning capacity, immediate fault inspection, it is easy to implement and its cost is low.	Unknown
[46]	A multi-camera measurement system using dynamic spatial data stitching	The elimination of time-consuming wiring and expensive sensors. The full field measurement over a large area and the need for large channel data acquisition systems.	A full surface of a WTB is not inspected. It requires to set the accuracy of the method with more than two pairs of cameras.
[48]	Non-contact vibration monitoring of rotating WTs using a semi-autonomous UAV with a digital image correlation system	Monitoring of the WTBs in operation under real conditions	Wind conditions can affect the correct operation of the AUV. The vision flight mode must be programmed for each specific turbine.
[49]	Automatic detection of WTB surface cracks by UAV	Better performance than other classifiers based on similar feature sets. The effectiveness of the WTB crack detection method was demonstrated.	The method needs to be verified in real WTB.

[50]	Images from UAV together with a photogrammetric payload to perform the visual reconstruction of the WTB and its condition	It was validated for identifying and locating cracks in WTBs	To increase the accuracy.

3.2. Ultrasonic Testing

Ultrasonic testing is used to detect internal and external faults in WTBs, e.g. delamination, cracks, etc. [51,52]. The propagation of ultrasonic waves along the WTB leads to determine its condition [53,54]. Figure 3 shows an example of ultrasonic sensors located in WTBs and WT foundation.

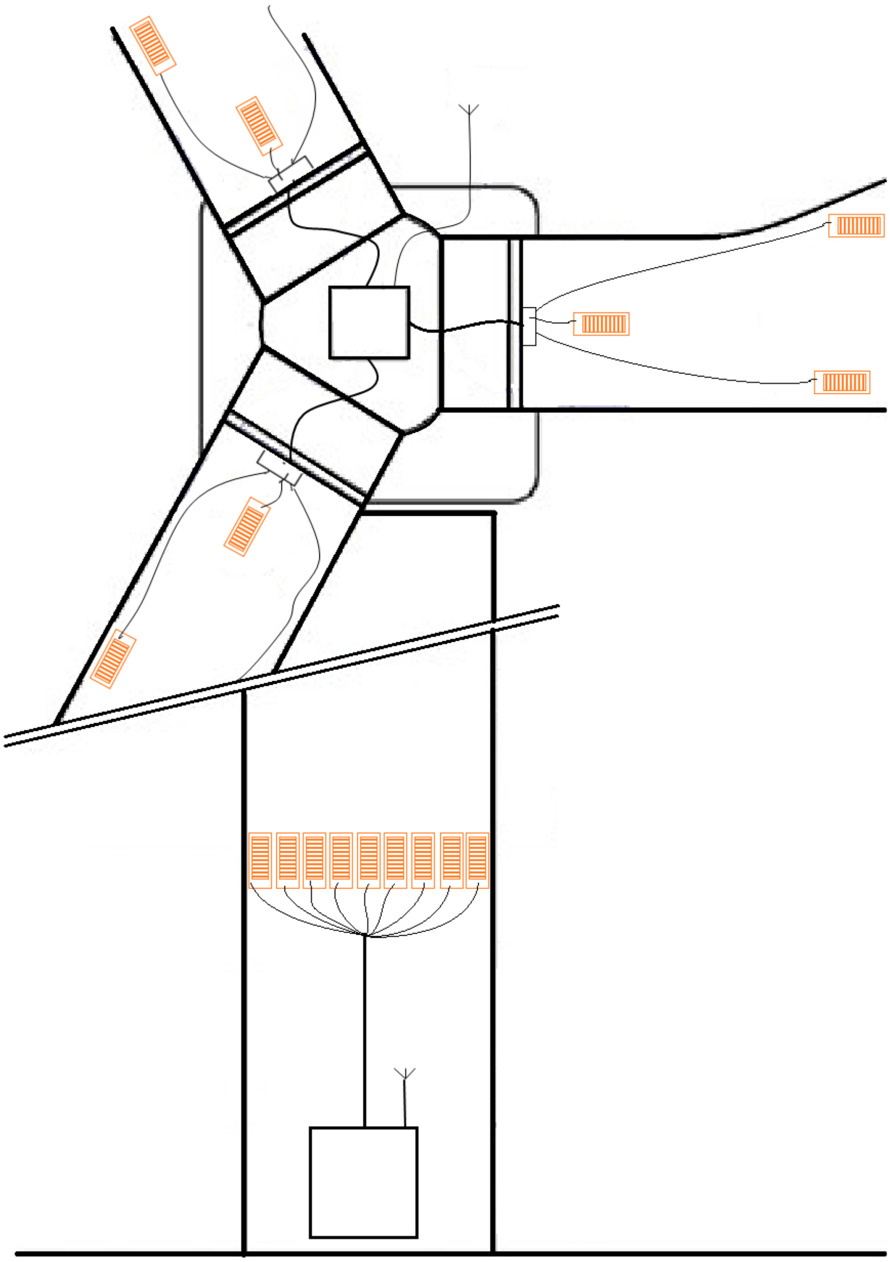

Figure 3. Wind turbine condition monitoring for WTB and tower.

Guided waves can travel long distances along the thickness of the WTB. These types of waves require signal analysis to identify and characterize faults. They involve dispersive and scatter guided wave modes. Tiwari and Raisutis [55] combined a transducer composed of macro fiber and air-coupled transducers to transmit and receive ultrasound-guided waves. Subsequently, signal processing techniques were applied for the analysis and characterization of the faults. Yang et al.[56] compared non-linear acoustics and guided wave techniques. The first one was insensitive to WTB faults. The guided wave method was able to detect and locate the faults by using the network of novelty detectors methodology.

Liu et al. [57] utilised an automatic positioning system in real time to measure the coordinates in working conditions. The system had an ADNS-3080 optoelectronic chip, a power conversion module and an USB transmission module. The results had a good accuracy. Li et al. [58] considered the adhesive quality inspection of wind rotor blades using thermography.

Park et al. [59] proposed a two-level scanning system to minimise the time to inspect WTB: first level, a basic scan with low resolution is employed to locate the delamination, and; second level, if the delamination is detected and locate, a high resolution scan is done where the delamination was found. Moll et al. [60] used radar sensors permanently installed in the WT tower for WTB remote condition monitoring. The experiments were done in the laboratory, detecting faults with good accuracy.

WTBs may also present wrinkles on their surfaces. Larrañaga et al. [61] studied 3 different ultrasound techniques to study this phenomenon: full matrix capture (FMC) together with the total focus method (TFM); a commercial phased-array ultrasound instrument, and; a single element immersion test. The results showed that the best results are obtained with the FMC/TFM method.

Arnold [60] demonstrated experimentally that a bistatic frequency-modulated continuous wave (FMCW) radar can detect a 30 mm cut-off in the fiberglass composite structure. It was also located an accumulation of water.

Although ultrasonic NDT are used effectively, the different layers of the WTB cause noise in the signals, making it difficult to detect and locate faults. Nowadays, there are different techniques for automatic processing of ultrasonic signals to increase the reliability and accuracy of these tests. Tiwari et al. [62] considered three techniques: wavelet transform, cross-correlation methods and Hilbert-Huang transform. It is concluded that a hybrid system of these methods obtains the better solutions than the use the technique individually. In 2018, they employed a low-frequency ultrasonic system to detect and analyse faults in WTB [63]. Discrete wave transformation, variational mode decomposition and Hilbert transformation were also applied for ultrasonic signal processing. A new hybrid signal processing technique is applied by Tiwari et al. in [64]. Cross-correlation and wavelet transformation techniques are combined to determine the size and location of the faults. The results show that the fault is independent of the scattering characteristics of the guided waves.

The fault detection method depends on the size of the faults, the distance between the transducers and the excitation frequency. Arcos et al. [65,66] utilised advanced signal processing and machine learning to calculate the thickness of dirt and mud on a WTB. They demonstrated that the combination of the k-nearest neighbours (KNN) with the principal component analysis (PCA) was the best approach for mud detection and diagnosis.

Brett et al. [67] proposed an ultrasound technique with a frequency lower than 100kHz. It led to map the resonances of the structure and the possible failure conditions in WT foundations. The experimental results, together with mathematical models, demonstrated the viability of the technique to be employed also in WTB.

Hermosa et al. [68] employed Macro-Fiber Composite transducers for FDD by means of ultrasound signals processing. They employed wavelet transforms, where the energy was used for pattern recognition.

Lamarre [69] used a phased ultrasonic system for WTB inspections with low frequency sensors. Faults could be detected and set the size of faults such as wrinkles, delamination and adhesive thickness. This technique allowed a fast inspection, small resolution and full coverage of the inspected area. Li et al. [70] studied the quantitative relationship between millimeter-scale disunion faults and ultrasonic parameters. Table 2 summarises the main strengths and weaknesses of the methods based on ultrasonic testing.

Table 2. Ultrasonic Testing methods applied to WTB: Strengths and Weaknesses.

Ref.	Method	Strengths	Weaknesses
[51]	Wavelet transforms and pattern recognition on ultrasonic guides waves	The method can detect ice on WTB with a low computational cost	The method needs to be applied in real cases.
[52]	SHM for delamination detection and location employing guided waves	The methodology employed is capable of detecting WTB faults at an early stage.	A study is needed to implement a network of sensors arranged in a strategic way for the detection of faults, cracks or disbonds.
[53]	Guided wave signal processing and pattern recognition through automatic learning	The method can detect and diagnose delamination in WTB, with a good accuracy.	Unknown
[55]	Refinement of fault detection using guided waves	The guided waves cover long distance along the thickness of the structure	The guided waves can be dispersive, superimposed and scattered. Signal processing techniques are necessary
[56]	Guided wave SHM techniques by network of novelty detectors	Possibility to create a network of low numbers of sensors and actuators for WTB-SHM.	There are problems with the power supply to the transducers.
[71]	Automatic positioning system of ultrasonic testing	Automatic positioning system to determine the coordinates and distance of the target in real time	Need of components such as LEDs, lenses, microprocessor, optical sensors, etc.
[61,64]	Adaptive time-of-flight analysis of noncontact laser ultrasonic signals	It detects delamination in WTB quickly.	Two levels of scanning are needed for the implementation of the method.
[60]	Radar-based SHM of WTB	The efficiency of the radar methodology for the WTB SHM was demonstrated. The presence of water on the WTB was successfully detected.	No changing environmental conditions or variable operating conditions were considered.
[61]	Wrinkle measurement in glass-carbon hybrid laminates	The method of full-matrix capture and the total focusing	Not all techniques allow the characterisation of off-

	comparing ultrasonic techniques	method provided better results.	plane waviness in hybrid glass-carbon laminates.
[62]	Signal processing methods to improve the signal-to-noise ratio	A hybrid signal processing method is proposed to improve fault detection.	Cross-correlation is not efficient in reducing noise. The Hilbert Haung transformation is limited by intrinsic mode selection.
[63]	Post-processing of ultrasonic signals for the analysis of faults using guided waves	Signal processing techniques are suitable for improving fault analysis.	Only one side of the WTB segment was accessed.
[64]	Hybrid signal processing technique to improve the fault detection	The wavelet transforms and cross-correlation techniques are combined in order to extract the size and location of the faults and time delays	Only one side of the sample was accessed
[65]	Fault diagnosis employing guided waves and supervised learning classifiers to detect dirt and mud on a WTB	The proposed methodology can detect and classify the levels of mud considered in the experiment.	Two scenarios have been studied; the best classifier is different for each case. Therefore, the classifiers should be evaluated for each specific case.
[66]	Detection and classification of ice thickness based on pattern recognition through guided ultrasonic waves and automatic learning	The methodology used obtains ice detection results with excellent predictive accuracy. Twenty linear and non-linear classifiers of Machine Learning were used.	Needs (?) To be applied in real cases.
[68]	Fault detection and diagnosis method based on the wavelet transform to detect faults	The method provides an accurate position of the early fault and allows excellent preventive and predictive maintenance planning.	It can lose information by filtering and post-processing.
[69]	Accessible advanced ultrasonic phased array technology	The small resolution, fast inspection speed, and full coverage of the inspected area.	Expensive hardware is required. Only the Olympus brand has been analysed.
[70]	Quantitative research into millimetre-scale debonding faults by using ultrasonic inspection.	Ultrasonic testing is effective in detecting faults in the bonding of composite materials.	The method was applied by simulation and it can serve as a reference for future experiments.

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The NDT ultrasound technique has been demonstrated to be able to detect external and internal faults in the WTB surfaces. This technique requires new research for the continuous monitoring of faults. It is also needed to continue researching in robust and efficiency algorithms, mainly based in artificial intelligence, due the amount and complexity of the data.

3.3. Thermography Testing

Thermography presents some problems to be used in WTB, e.g. misinterpretation of thermograms caused by reflections, dirt, etc. Doroshtnasir et al, [72] employed a method to minimize the disturbing influences analysing the WTB photographic images together with thermogram difference images. This technique can detect possible subsurface faults from the ground, aircraft or ships.

Infrared analysis is an NDT that can inspect large surfaces in a short time. It was employed by Ramirez et al. [73] considering different scenarios over the WTB surface (see Figure 4). Avdelidis et al. [74] shown the advantages and limitations of the infrared thermography technique, they studied its use in the inspection and evaluation of WTBs.

Worzewski et al. [75] employed several thermographic experiments on a glass fibre reinforced plastic (GFRP) stepped wedge and on a defective rotor WTB segment. The results showed that GFRP thicknesses of 3 cm can be detected only by solar heating. The experimental results were studied together with finite element method (FEM).

Lizaranzu et al. [76] studied a set of patterns in several materials by active thermography and patterns recognitions. They concluded that thermography is a technique of easy configuration, without the need of contact, the inspection times are shorts and it allows large areas to be inspected. The results depend on the resolution of the thermographic camera, the minimum size/accuracy ratio of faults and the heat sources.

WTB have also been studied in working conditions. Hwang et al. [77] analysed the WTB fault detection under rotating condition. They used a continuous line laser thermography system together with an algorithm to analyse faults. Although the sensor based ultrasonic technique generated noise on the signals, the noise was filtered, and false alarms were not found. Reference [78] proposed a continuous line laser scanning thermography system and a visualization algorithm for remote inspection of internal delamination in WTB. The results showed that the WTB can be quickly inspected and the internal delamination can be visualised without contact and autonomously. The visualization algorithm extracts the delamination without any false alarm.

Dollinger et al. [79] studied the measurement uncertainty with three algorithms in sunny and cloudy environmental conditions. The results showed that the measurement uncertainty is limited to the flow characteristics of the boundary layer. The accuracy of the location depended on the temperature difference between the flow regimen and the width of the transition region.

The aerodynamic performance of WTBs depends on the condition of the leading edge. Thermographic measurements allow a characterization of the leading edge condition. Dollinger et al. [80] demonstrated that post processed thermographic flow visualization measurements together with image processing algorithms allow the non-invasive localization of the laminar-to-turbulent transition position.

Martin et al. [81] utilised infrared thermography, inverse terahertz synthetic opening radars and X-ray imaging. The research was done in the WTB manufacture, showing the advantages, disadvantages and future challenges for each technique.

The glue structure is under more stress due to the WTBs being bigger and, therefore, its quality must be studied. The glue employed in WTB was studied by means of transmission thermography in reference [58]. Three different glue thicknesses were considered. The approaches provided results with good accuracy.

Table 3 presents the main strengths and weaknesses of the methods based on thermography testing.

Table 3. Main methods based on thermographic testing in WTB: Strengths and Weaknesses.

Ref.	Method	Strengths	Weaknesses
[72]	On-site inspection with thermography	The method detects possible WTB subsurface faults from greater distances than others.	The method uses particular WTB thermograms. In the future it is recommended that WTB be recorded automatically, therefore, thermograms can be in the correct angular position.
[75,82]	Thermographic inspection of a WTB utilizing natural conditions as excitation source	It demonstrates that the sun is an enough heat source to apply thermography on GFRP	FEM simulations have a sensitive variability regarding physical and environmental properties, that affect the thermographic images.
[76]	Analysis by transient active thermography of a set of inspection patterns.	Thermography is an efficient method for fault detection in composite materials. It is easy to set up, is a non-contact technique, and inspection times are short.	This technique is limited by the depth, dimensions and nature of the faults. It involves a distortion of the heat flow of the test piece.
[77]	Continuous line laser thermography for damage imaging of rotating WTB	The proposed method achieves fast and in-situ non-contact failure images, automatically and in a rotating condition.	It is proposed to improve inspection speed and damage depth estimation
[78]	Continuous line laser scanning thermography for remote internal delamination inspection at WTB	The performance of the technique was validated experimentally and with a large-scale test (3 MW WT).	The detection range can be improved by further adjusting the laser beam intensity and the viewing angle of the infrared camera
[58]	Adhesive quality inspection	The results showed that transmission thermography is effective in determining the quality of the adhesive.	Only applied to laboratory experiments.
[79]	IR thermographic flow visualization measurements for transition detection on WT in operation	Measurements are possible at a working distance of several hundred meters. The proposed algorithm allows the location of the transition with sub-pixel precision.	The location accuracy depends on the temperature difference between the flow regimes and the width of the transition region.
[80]	Quantification of boundary layer flow disturbances due to the leading-edge condition	The measurement method can be used during operation and allows a characterization of the leading-edge condition.	A long-term measurement campaign to measure the seasonal impact of boundary layer disturbances is recommended as future work.

The main thermography techniques are: instantaneous thermography; pulsed thermography; pulse phase thermography; ultrasonic blockade thermography, and; modulated thermography. Each of these types depends on the specific input of the system. Thermography is increasing as an NDT technique for composite materials. This class of technique can detect delamination faults with an accuracy comparable to other techniques [81]. The results show that they can detect adhesive faults, delamination and mechanical loading.

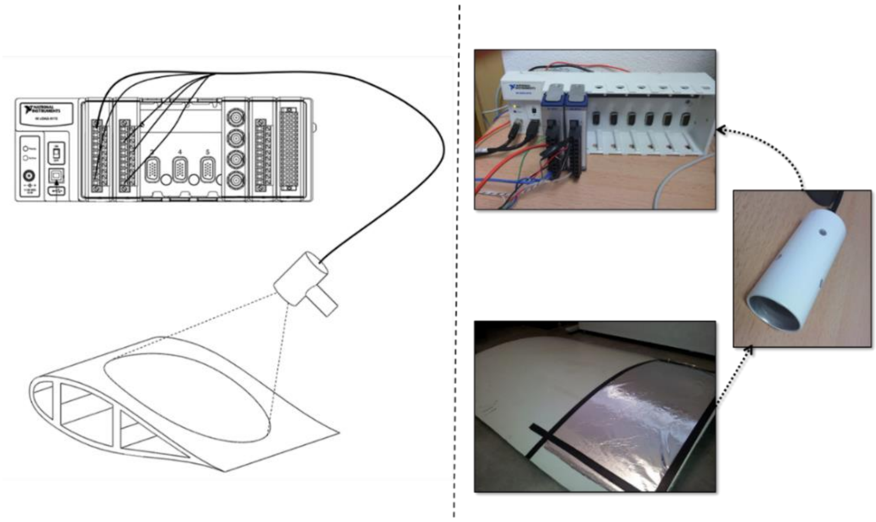

Figure 4. Scheme of the experimental set up for ice detection by thermal infrared radiation [73].

3.4. Radiographic Testing

Radiographic testing is an efficient NDT method to detect internal faults in polymer foam core sandwich panels [83]. Computed tomography (CT) use has increased in the last decade, due to improvements in spatial resolution, increased availability of X-rays and reduced acquisition time [84]. X-ray CT systems allow experimentation and capture processes in-situ and in real time (up to 20 tomograms per second). Chen [85] proposed to examine the fractographic characteristics by optical miscroscopy and X-ray CM. Fractographic analysis identifies failure modes by studying sandwich panels with slotted spiral cores. The results show that the fiber rupture occurs in the bleaching region, although it cannot be visually appreciated. Radiography has been also employed in bearings. Reid et al. [86] have proposed the images from the Neutron Bragg edge to obtain two-dimensional mapping to detect the plastic deformation. The results showed that there is a strong correlation between the load and the width of the Bragg rim.

Fiber orientation in WTB materials is essential because the compressive strength of the composite is directly related to the fiber orientation. Emerson et al.[87] proposed a segmentation method to accurately extract individual fibers by X-ray tomography.

Fantidis et al. [88] employed a transportable radiography testing system to analyze WTBs. A transportable neutron radiography system, incorporating an Sb–Be source, was considered using the MCNPX code with a wide range of radiography parameters.

Jasinien et al. [89] adapted ultrasonic and radiographic techniques. The novelty of the study is based on the combination of immersion techniques using a moving water container and contact pulse-echo. The approach could detect shape and size of faults. They employ pattern recognition to both ultrasonic and radiographic techniques, where the faults could be found.

X-ray laminography is designed to provide 3D information of the WTB. Mikkelsen [90] used an X-ray detector to improve the amount of information obtained from the laminogram reconstruction. Then, a material decomposition algorithm was applied to the data.

Table 4 shows the main radiographic testing methods applied to WTB, considering the strengths and weaknesses.

Table 4. Main radiographic testing methods applied to WTB: Strengths and Weaknesses.

Ref.	Method	Strengths	Weaknesses
[84]	X-ray computed tomography of polymer composites	Reduced acquisition time and improved spatial resolution.	Low resolution
[85]	Fractographic analysis of WTB using optical microscopy and X-ray computed tomography	The fractographic characteristics allow the identification of the failure process and the causes of future WTB failure.	The sandwich structures of the WTBs must be studied for manufacturing induced faults that are unavoidable.
[87]	The method is able to extract individual fibres to calculate their orientation	It obtains accurate results regardless of image quality.	Sometimes it is not possible to obtain high quality images due to long scanning times.
[88]	Transportable radiography system	Transportable X-ray is able to detect faults in WTB and reduce the cost of inspection.	Unkown
[89]	Adapted ultrasonic and radiographic techniques for WTB	The radiographic techniques efficiently detect structural faults within WTB.	Better results are achieved with the combination of radiographic and ultrasonic techniques.
[90]	X-ray computer tomography	X-ray CT is able to detect the fault evolution due to the stiffness properties of composite materials.	The evolution of fatigue damage depends on the type of load and the architecture of the fiber reinforcement.

X-ray test is commonly used as NDT method. Delamination can be seen in radiographic testing if the orientation is not perpendicular to the x-ray beam. There are many types of X-rays. Gamma-ray radiography is used for thicker parts because it has shorter wavelengths. X-ray tomography is a technique that is increasing in use, leading to study interior characteristics of the material. The new digital tomography systems allow 3-D visualization. There are many research studies that are appearing applied to WTB, and it is expected to continue the growth.

3.5. Electromagnetic Testing (ET)

Electromagnetic waves are used in NDT and SHM applications with microwave and millimeter wave frequency range [91]. Li et al. [92] proposed a microwave scanning method to detect delamination in WTB. The reflected electromagnetic signal shows changes in the composite cross-section, using an open-ended waveguide sensor. The results demonstrate that it can be an efficient technique to monitor the WTB for the manufacturing process. However, it is difficult to implement this technique due to the height of the WTB.

Electromagnetic technology is sensitive to changes in conductivity and is non-invasive. Zhao et al. [93] proposed an NDT based on the electromagnetic measurement technology of carbon fiber reinforced polymer. This type of polymer is an advanced non-metallic composite material constructed from a carbon fiber reinforced polymer resin, which is used in the WTB for its high potential strength, anti-corrosion, light weight and good fatigue resistance. The results obtained demonstrated the effectiveness for the detection of WTB surface cracks.

Im et al. [94] employed the characterization and inspection techniques at the edges of WTBs by TeraHertz (THz) waves. These signals, in the time domain spectroscopy mode, have some similarities to ultrasound waves, with the disadvantage that a THz pulse cannot penetrate a material with conductivity. However, the images have higher resolution, being an emerging NDT technique in WTB [95].

Moll et al. [96] applied a radar imaging system to WTBs. It is based on two continuous wave and frequency modulated radar (FMCW) sensors to monitor the WTBs in real time. They proposed to test with a transmitter and nine receivers for studying delamination, cracks, etc., in operating WTBs.

Similar approaches can be also employed in other WT components, for example: there is an intrinsic electromagnetic vibration caused by an alternating magnetic field on a low rigidity stator, which modulates the vibration signals of the generator and makes it difficult to remove the cause of bearing failure. It can appear when there is a fault in a bearing. Teng et al. [97] deduced that electromagnetic vibration can be a disturbance source which makes difficult to achieve the characteristics of the fault. Esmaeili et al. [98] investigated the interference of Doppler echoes caused by WTs, as it affects meteorological radar stations. They presented a bistatic FMCW radar with a flexible and economical design together with the IQ-mix method. They are approaches to be consider in WTBs.

Table 5 summarises the main electromagnetic testing methods applied to WTB, considering the strengths and weaknesses.

Table 5. Main methods based on electromagnetic testing in WTB: Strengths and Weaknesses.

Ref.	Method	Strengths	Weaknesses
[91]	Electromagnetic waveguides for faults detection by numerical and experimental analysis	Faults, e.g. cracks, can be detected.	A perpendicularly oriented crack is more detectable than a coaxially aligned crack to the direction of wave propagation.
[93]	Measurement of CFRP surface by electromagnetic measuring	The method shows results with good accuracy.	More information about crack condition is necessary.
[94]	Characterization and inspection techniques of trailing edges in WTB using THz waves	This method can measure the refractive index using THz-waves for WTB inspection.	THz-waves are limited by the axial direction of the material.
[95]	A review about THz NDT	THz images have higher resolution than ultrasound images.	THz waves have less penetration than other methods.
[96]	Radar imaging system for in-service WTB inspection	Radar systems are capable to monitor WTBs in real time.	Other types of fault, such as delamination and cracks, should be tested in the future.

The THz-NDT technique allows a high-resolution for cross-sectional images. The THz has high sensitivity and resolution, and the tests are performed without the need of contact. The disadvantage is the high cost of the CMS, but the new technologies are leading to reduce it.

3.6. Acoustic Emission Testing

Acoustic emission is a technique employed for early damage detection [99]. It can analyze cases such as friction, rolling contacts formation and propagation of cracks, mainly in the frequency domain [100].

Acoustic emission tests are a good technique for monitoring glass fiber reinforced plastics, a common material in WTB. However, general acoustic emission sensors have certain limitations for these materials due to the low acoustic impedances. Kim et al. [101] compared various high sensitivity acoustic emission sensors for glass reinforced plastic to achieve a broadband frequency spectrum.

Tang et al.[102] did an experimental study of the acoustic emission technique for monitoring the service state of WTB. A signal processing algorithm was applied considering high noise level during the fatigue test for the location of the acoustic emission source. The results showed that the cracks were successfully detected, and also early warnings.

Saeedifar et al. [103] have used a combination of acoustic emission technique and the dispersion reduction method to determine the position of the delamination in WTBs.

Gómez et al. [104] employed a heuristic method for detecting and locating faults with acoustic transducers. It was done in real WTBs. The sensors employed were the electromagnetic acoustic transducers type. They filtered the signal noise by wavelet transforms. Finally, they did multi-parametric analysis for fault classification, and analysing the attenuation of the curves for fault localisation.

Several piezoelectric acoustic emission sensors are employed to monitor WTBs components that support the load of the structure, generating a large amount of data. This data must be processed automatically for fault detection. Angelopoulos et al. [105] showed several algorithms that were useful for unsupervised collection of acoustic emission data. Tang et al. [106] utilised the acoustic emission by piezoelectric sensors. The signals were analysed by a K-mean clustering algorithm and pattern recognition method. The failure modes were classified accurately.

Xu et al. [107] developed a robust fault mode identification of adhesive composite joints for WTB using acoustic emission and machine learning. The clustering method was based on fast search, that could find density peaks. It was applied as pattern recognition of acoustic emission signals. A similar research work was done by Liu et al. [108] under accelerated fatigue loads in WTBs.

The foreign object impact was detected by acoustic emission and radical basis function neural network by Wang et al. [109]. The study was done in time and frequency domain analysis.

Statistical parameters, as root mean square and experimental modal parameters, were employed for fault detection in WTB by Doliński et al. [110]. The rotor displacements of WTB rotors perpendicular to the rotor plane was studied by the ten first mode shapes of bending vibrations.

Liu et al. [111] studied a WTB bearing with low speed by acoustic emission analysis. Fuentes et al.[112] proposed a method using acoustic emissions and probabilistic modelling for the detection of subsurface damage in WTB bearings.

Marks et al. [113] studied experimentally the use of Lamb waves to monitor the SHM of a WTB. They used a Laser vibrometer of 3D scanning to study Lamb waves. They also applied different signal processing methods to locate accurately the fault. It was concluded that acoustic and ultrasonic techniques are robust, effective and reliable for SHM of WTBs.

Wilkinson et al. [114] applied a low frequency acoustic and ultrasonic wave technique for SHM in aerial and aquatic environments. The results have shown that the acoustic system needs approximately 90-100dB, however the ultrasound system only requires about 40dB to obtain accuracy results.

Cracks are being detected in WTB by using a single microphone, or a set of microphones. Poozesh et al. [115] employed an audio microphone inside the WTB and they monitor the sound. They could detect cracks in WTB with accuracy.

Table 6 presents the main acoustic emission testing methods applied to WTB, considering the strengths and weaknesses.

407 **Table 6.** Main methods based on acoustic emission and ultrasonic testing in WTB: Strengths and
408 Weaknesses.

Ref.	**Method**	**Strengths**	**Weaknesses**
[102]	CMS of WTB fatigue.	The AE signals correlated with the growth of delamination.	An optimal sound threshold should be selected to avoid/reduce false alarms.
[103]	Prediction and propagation of delamination by AE analysis and implementation of bi-linear and tri-linear cohesive zone models.	The combination of AE and tri-linear cohesive zone modelling, predicts the initiation and propagation of delamination in laminated composite materials.	The bi-linear cohesive zone modelling cannot predict the initiation and propagation of delamination.
[104]	Signal processing for fault identification, detection and sizing with electromagnetic acoustic transducers.	The results present good accuracy.	It should be tested in real case studies.
[106]	A pattern recognition approach to study the WTB fatigue.	AE signals characterize failure modes in composite materials.	To improve the accuracy.
[107]	AE analysis by clustering analysis by machine learning.	Robust identification for different faults by pattern recognition and AE signal analysis.	The classification results depend on the cut-off rate. Adhesive layer shear failure is the least sensitive failure mode.
[108]	Identification of WTB fault mode under accelerated fatigue loading using AE and automatic learning	Sources of local AE faults are successfully detected.	WTBs in service require more AE sensors.
[109]	Identification of foreign objects based on AE, domain analysis, time domain analysis, frequency and radical base function neural network	The method is validated, and present good accuracy.	Requires to be tested in a real case study.
[110]	Damage detection in WTB using root mean square and experimental modal parameters	Modal parameter monitoring is able to determine the technical condition of the structure. The method is effective for fault detection using vibration modes.	The modal parameters are analysed only experimentally. The research was carried out in a small-scale WTB.
[112]	Detecting sub-surface damage using AE measurements and Gaussian mixture models	Fault detection below the surface of a planetary gearbox bearing. The detection was made under	AE measurements depend on load, temperature and lubrication.

		changing operational and environmental conditions.	
[111]	Fault diagnosis of WTB bearing using AE analysis	The method is validated and offers a solution for wind farm applications.	The fault signals are weak and are masked by large noise disturbances.
[101]	Comparison of AE sensors for glass fiber reinforced plastics	Good accuracy in short distances.	General AE sensors have limitations in monitoring composite materials due to low acoustic impedances.

AE technique is a passive NDT technique, where elastic wave sources are emitted by the material under study and not by an excitation source [116]. These waves indicate microstructural changes of WTBs such as fiber breakage, cracking, disunion, crack initiation, and delamination. The use of guided waves for SHM is increasing. Most of the researches require to be implemented in real cases. Figure 5 shows an example of piezoelectric sensors located in a WTB section for acoustic emission testing and fault detection and location by triangulation.

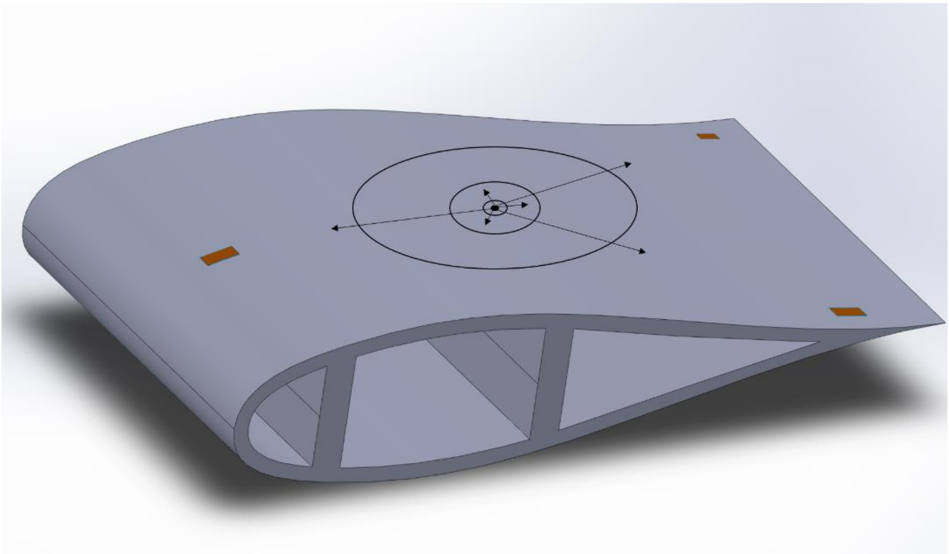

Figure 5. Wave front propagation from the acoustic emission source.

3.7. Shearography Testing

Shearography is used to visualize variations in surface deformation by interfering with laser point patterns. It is a robust technique against external vibrations for an interferometric system [117]. Shearography includes digital shearography, with high sensitivity that can be combined with different optical configurations, and studied by phase change algorithms and other techniques [118]. Macedo et al. [119] employed a novel shearography system with radial sensitivity to analyse the internal surfaces of the flanged joints of composite materials. Experimental results show that this technique can detect faults due to adhesion in flanged joints. Ye et al. [120] used an automated shearography system with thermal excitation. Their method allowed automatic inspection of the heatproof outer coating attached to the component.

Shearography obtains high precision in short time, and it is also full-field and non-contact imaging [121]. Therefore, it is suitable for fast and reliable inspections of WTB [122]. This technique has a limited sensitivity to delamination faults in the thicker parts. Another drawback is expensive and complex equipment needed [123].

Table 7 shows the main shearography testing methods applied to WTB, taking into account the strengths and weaknesses.

Table 7. Main methods based on shearography testing in WTB: Strengths and Weaknesses.

Ref.	Method	Strengths	Weaknesses
[119]	Shearography with radial sensitivity	It detects adhesion faults on internal surfaces.	The radial displacement is not adjustable.
[120]	An automated shearography system for cylindrical surface inspection	It can identify bonding faults on the cylindrical surface. Automated inspection is more efficient and accurate than manual inspection.	A comprehensive training package is necessary to improve automatic recognition.
[121]	Internal fault detection method for composite insulators	High-speed, non-contact, full-field and high-precision imaging	It was only tested in laboratory.
[122]	Method applied to composite materials with impact damage.	The damage can be located with good accuracy.	The loading time has a robust influence on the result.
[123]	Delamination detection in WTB	The vacuum load is correct for delamination detection	The vacuum pressure depends on the type of material and the properties of the fault. The load parameters must be defined for each type.
[118]	Digital shearography	Simple configuration and low sensitivity to environmental disturbances.	It offers a phase map with a lot of noise that reduce the fault detection accuracy.

Shearography is applied to measure the deformation gradient, detecting faults better than other NDT techniques because of the stress concentration done by the fault. Shearography can measure in real time and full field. This technique has a simple configuration and offers direct measurement of stress. It is insensitive to the environment. Shearography is not able to detect faults far from the surface. Shearography is not a mature technique yet and requires future research.

3.9. Other NDT Testing

Mikkelsen [124] analysed fibre failures in WTB by X-ray technique and cross-sectional scanning. It was applied for fault detection in cases where the unidirectional fibre bundles are in contact with reinforcement fibre bundles.

The VITCEA European project utilises shearography, thermography and ultrasounds for studying the carbon and glass fibers condition [125]. Delamination and flat bottom orifice of carbon textile (CFRP) and Glass textile (GFRP) fiber reinforced polymer (FRP) materials with unidirectional fiber and quasi-isotropic were considered. Experimental data was studied by pattern recognition with both analytical and numerical models. It was based on data analysis by thermal contrasts together with phase evaluation techniques. Strugała et al. [126] introduced a new NDT method for low energy impact damage in CFRP. It is based on the thermo-optic effect employing a laminated film of thermochromic liquid crystal (TLC). The results are validated with other techniques such as computerized radiography and active thermography.

Hyperspectal imaging, also called image spectroscopy, is considered as an NDT. This technique is fast in remote sensing, and it is used for fault detection and diagnosis. Rizk et al. [127] used this method for fault and ice detection. The results showed that hyper-surface imaging can detect fault in surface and subsurface, and also early ice formation.

Baqersad et al. [128] presented a survey in photogrammetry and optical methods in structural dynamics. The authors concluded that these technologies should be work in real time.

Iliopoulos et al. [129] utilised ultrasonic pulse velocity (UPV) and X-rays for SHM The data were studied by signals correlations.

4. Outlook of the technology

Offshore wind industry has a high percentage of the O&M total costs, being most of them invested in unplanned failures. To reach a competitive industry, new approaches in maintenance are required, e.g. CMS to TES. It is extended to WTB, where the size has increased in recent years, leading higher failure probability, i.e. costs and downtimes to the industry.

This manuscript has presented and analysed the state of the art of NDT on WTB. It can be concluded that there are a large number of NTD techniques employed and developed in this field.

Macroscopic failure and microscopic fractographic morphologies by mean of X-ray computed tomography and radiography are being employed, but they require new advances because they are costly and require a long time to inspect the WTBs. There are also new techniques that are beginning to be employed, e.g., electromagnetic testing, shearography, photogrammetry, spectroscopy, radar imaging system, etc.

Ultrasonic testing and acoustic emission have been and will be the most employed technique to inspect WTD on, in and into the surface, but generate a signal that requires complex analytics.

Most of the mentioned NDT techniques require to stop the WT. The new advances are going to employ they online, without any stop of the WT, and considering different techniques together to increase their accuracy. NDT systems embedded in UAVs are being to be designed and developed for this purpose employing, for example, images, thermography, photogrammetric, etc.

Finally, CMS will use new sensors, that will generate variety a large amount of data, that will need of advanced analytics and to be studied together with SCADA data [130]. The survey shows that the new approaches are mainly focused on artificial intelligence and architecture of algorithms.

6. Conclusions

Any fault in wind turbine blades generates important downtimes, costs and energy production loss. Nowadays, new condition monitoring systems are appearing for Non-Destructive Testing applied to wind turbines blades. This paper has summarised and analysed the most important advances done in this field in the last few years. They are mainly based on visual, ultrasonic, thermography, radiography, electromagnetic, acoustic emission, acoustic- ultrasonic, shearography and other non-destructive techniques.

Visual inspection presents low accuracy regarding to other non-destructive techniques. Visual inspections of wind turbine blades are not easy because of the high height of them. Visual inspection does not detect internal faults. Cameras with big zoom or digital cameras with long range lenses are used for visual inspection, together with devices embedded in unmanned aerial vehicles.

Ultrasonic techniques are the most employed in wind turbine blades. They have demonstrated robustness and accuracy for fault detection and diagnosis, both internal and external faults to the surface.

Passive thermography can monitor wind turbine blades from the ground in wind turbine operation. Heat flows caused by periodic loading and faulty areas can be analysed with this technique. Active thermography needs thermal excitation.

X-ray testing transmits ionizing radiation into a material and its attenuation is measured for fault detection. The X-ray allows the detection of internal faults such as cracks, thickness variations, corrosion, etc. It can be used in 2D or with 3D mode tomography.

Electromagnetic testing is a non-contact technique with high resolution. It has great impact as a non-destructive technique for detection in metal components.

Acoustic emission allows to detect and identify damages in wind turbine blades. A large number of studies have shown the efficiency of this method.

Shearography is able to detect surface deformation. The efficiency depends on the size and location of the faults. The technique is being employed due to the technological advances done in cameras, laser sensors and hardware.

Acknowledges: The work reported herewith has been financially supported by the Dirección General de Universidades, Investigación e Innovación of Castilla-La Mancha, under Research Grant ProSeaWind project (Ref.: SBPLY/19/180501/000102). The authors are very grateful to Alfredo Peinado for his English review.

References

1. Vallterra, M.C. La disolución de la comunidad europea del carbón y del acero: Estado actual. *Revista de Derecho Comunitario Europeo* **2002**, *6*, 393-432.
2. Snyder, B.; Kaiser, M.J. Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy* **2009**, *34*, 1567-1578.
3. García Márquez, F.P.; Pliego Marugán, A.; Pinar Pérez, J.M.; Hillmansen, S.; Papaelias, M. Optimal dynamic analysis of electrical/electronic components in wind turbines. *Energies* **2017**, *10*, 1111.
4. Menezes, E.J.N.; Araújo, A.M.; da Silva, N.S.B. A review on wind turbine control and its associated methods. *Journal of Cleaner Production* **2018**, *174*, 945-953.
5. Ruiz, M.; Mujica, L.E.; Alférez, S.; Acho, L.; Tutivén, C.; Vidal, Y.; Rodellar, J.; Pozo, F. Wind turbine fault detection and classification by means of image texture analysis. *Mechanical Systems and Signal Processing* **2018**, *107*, 149-167.
6. Asensio, E.S.; Pérez, J.P.; Márquez, F.G. In *Economic viability study for offshore wind turbines maintenance management*, Proceedings of the Ninth International Conference on Management Science and Engineering Management, 2015; Springer: pp 235-244.
7. Igba, J.; Alemzadeh, K.; Durugbo, C.; Eiriksson, E.T. Through-life engineering services of wind turbines. *CIRP Journal of Manufacturing Science and Technology* **2017**, *17*, 60-70.
8. Junior, V.J.; Zhou, J.; Roshanmanesh, S.; Hayati, F.; Hajiabady, S.; Li, X.; Dong, H.; Papaelias, M. Evaluation of damage mechanics of industrial wind turbine gearboxes. *Insight-Non-Destructive Testing and Condition Monitoring* **2017**, *59*, 410-414.

9. Pedregal, D.J.; García, F.P.; Roberts, C. An algorithmic approach for maintenance management based on advanced state space systems and harmonic regressions. *Annals of Operations Research* **2009**, *166*, 109-124.
10. Márquez, F.P.G.; Pedregal, D.J. Applied rcm 2 algorithms based on statistical methods. *International Journal of Automation and Computing* **2007**, *4*, 109-116.
11. Márquez, F.P.G.; Muñoz, J.M.C. A pattern recognition and data analysis method for maintenance management. *International Journal of Systems Science* **2012**, *43*, 1014-1028.
12. Wang, Y.; Ma, X.; Qian, P. Wind turbine fault detection and identification through pca-based optimal variable selection. *IEEE Transactions on Sustainable Energy* **2018**.
13. Romero, A.; Soua, S.; Gan, T.-H.; Wang, B. Condition monitoring of a wind turbine drive train based on its power dependant vibrations. *Renewable Energy* **2018**, *123*, 817-827.
14. Pliego Marugán, A.; García Márquez, F.P. Advanced analytics for detection and diagnosis of false alarms and faults: A real case study. *Wind Energy* **2019**, *22*, 1622-1635.
15. Marugán, A.P.; Chacón, A.M.P.; Márquez, F.P.G. Reliability analysis of detecting false alarms that employ neural networks: A real case study on wind turbines. *Reliability Engineering & System Safety* **2019**, *191*, 106574.
16. García Márquez, F.P.; Segovia Ramírez, I.; Pliego Marugán, A. Decision making using logical decision tree and binary decision diagrams: A real case study of wind turbine manufacturing. *Energies* **2019**, *12*, 1753.
17. Pliego Marugán, A.; Garcia Marquez, F.P.; Lev, B. Optimal decision-making via binary decision diagrams for investments under a risky environment. *International Journal of Production Research* **2017**, *55*, 5271-5286.
18. Gómez, C.Q.; Villegas, M.A.; García, F.P.; Pedregal, D.J. Big data and web intelligence for condition monitoring: A case study on wind turbines. In *Big data: Concepts, methodologies, tools, and applications*, IGI global: 2016; pp 1295-1308.
19. Pérez, J.M.P.; Márquez, F.P.G.; Hernández, D.R. Economic viability analysis for icing blades detection in wind turbines. *Journal of Cleaner Production* **2016**, *135*, 1150-1160.
20. de la Hermosa Gonzalez, R.R.; Márquez, F.P.G.; Dimlaye, V.; Ruiz-Hernandez, D. Pattern recognition by wavelet transforms using macro fibre composites transducers. *Mechanical Systems and Signal Processing* **2014**, *48*, 339-350.
21. Jiménez, A.A.; Zhang, L.; Muñoz, C.Q.G.; Márquez, F.P.G. Maintenance management based on machine learning and nonlinear features in wind turbines. *Renewable Energy* **2020**, *146*, 316-328.
22. Marti-Puig, P.; Blanco-M, A.; Cárdenas, J.J.; Cusidó, J.; Solé-Casals, J. Effects of the pre-processing algorithms in fault diagnosis of wind turbines. *Environmental Modelling & Software* **2018**.
23. Marquez, F.G. An approach to remote condition monitoring systems management. **2006**.
24. Gomez, C.Q.; Garcia, F.P.; Arcos, A.; Cheng, L.; Kogia, M.; Papelias, M. Calculus of the defect severity with emats by analysing the attenuation curves of the guided waves. *SMART STRUCTURES AND SYSTEMS* **2017**, *19*, 195-202.
25. Márquez, F.P.G. A new method for maintenance management employing principal component analysis. *Structural Durability & Health Monitoring* **2010**, *6*, 89-99.
26. Muñoz, C.Q.G.; Marquez, F.P.G.; Liang, C.; Maria, K.; Abbas, M.; Mayorkinos, P. In *A new condition monitoring approach for maintenance management in concentrate solar plants*, Proceedings of the ninth

international conference on management science and engineering management, 2015; Springer: pp 999-1008.

27. Muñoz, C.Q.G.; Márquez, F.P.G. Future maintenance management in renewable energies. In *Renewable energies*, Springer: 2018; pp 149-159.
28. Rubert, T.; McMillan, D.; Niewczas, P. A decision support tool to assist with lifetime extension of wind turbines. *Renewable Energy* **2018**, *120*, 423-433.
29. Abraham, O.; Niederleithinger, E.; Chapeleau, X.; Klikowicz, P.; Brühwiler, E.; Bassil, A.; Wang, X.; Chakraborty, J.; Bayane, I.; Leduc, D. In *Addressing the need to monitor concrete fatigue with non destructive testing: Preliminary results of infrastar european project*, SMT and NDT-CE 2018, 2018; p 12p.
30. Abraham, O.; Ferria, H.; Niederleithinger, E.; Brühwiler, E.; Dalsgaard Sørensen, J.; Klikowicz, P.; Kirsch, F.; Niedermayer, H.; Yalamas, T. Infrastar-innovation and networking for fatigue and reliability analysis of structures-training forassessment of risk-h2020. *Impact* **2018**, *2018*, 70-72.
31. Chen, X. Fracture of wind turbine blades in operation—part i: A comprehensive forensic investigation. *Wind Energy* **2018**.
32. Gholizadeh, S. A review of non-destructive testing methods of composite materials. *Procedia Structural Integrity* **2016**, *1*, 50-57.
33. Yang, R.; He, Y.; Zhang, H. Progress and trends in nondestructive testing and evaluation for wind turbine composite blade. *Renewable and Sustainable Energy Reviews* **2016**, *60*, 1225-1250.
34. Martinez-Luengo, M.; Kolios, A.; Wang, L. Structural health monitoring of offshore wind turbines: A review through the statistical pattern recognition paradigm. *Renewable and Sustainable Energy Reviews* **2016**, *64*, 91-105.
35. García Márquez, F.P.; García ‐ Pardo, I.P. Principal component analysis applied to filtered signals for maintenance management. *Quality and Reliability Engineering International* **2010**, *26*, 523-527.
36. Yu, D.; Chen, Z.; Xiahou, K.; Li, M.; Ji, T.; Wu, Q. A radically data-driven method for fault detection and diagnosis in wind turbines. *INTERNATIONAL JOURNAL OF ELECTRICAL POWER AND ENERGY SYSTEMS* **2018**, *99*, 577-584.
37. Cho, S.; Gao, Z.; Moan, T. Model-based fault detection, fault isolation and fault-tolerant control of a blade pitch system in floating wind turbines. *Renewable Energy* **2018**, *120*, 306-321.
38. Koitz, R.; Wotawa, F.; Lüftenegger, J.; Gray, C.S.; Langmayr, F. Wind turbine fault localization: A practical application of model-based diagnosis. In *Diagnosability, security and safety of hybrid dynamic and cyber-physical systems*, Springer: 2018; pp 17-43.
39. Turnbull, H.; Omenzetter, P. In *Damage severity assessment in wind turbine blade laboratory model through fuzzy finite element model updating*, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, and Civil Infrastructure 2017, 2017; International Society for Optics and Photonics: p 101692E.
40. Turnbull, H.; Omenzetter, P. In *Comparison of two optimization algorithms for fuzzy finite element model updating for damage detection in a wind turbine blade*, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XII, 2018; International Society for Optics and Photonics: p 105991Q.
41. Dao, P.B.; Staszewski, W.J.; Uhl, T. Operational condition monitoring of wind turbines using cointegration method. In *Advances in condition monitoring of machinery in non-stationary operations*, Springer: 2018; pp 223-233.

42. Nielsen, J.S.; Sørensen, J.D. Bayesian estimation of remaining useful life for wind turbine blades. *Energies* **2017**, *10*, 664.
43. Stutzmann, J.; Ziegler, L.; Muskulus, M. Fatigue crack detection for lifetime extension of monopile-based offshore wind turbines. *Energy Procedia* **2017**, *137*, 143-151.
44. Kim, D.Y.; Kim, H.-B.; Jung, W.S.; Lim, S.; Hwang, J.-H.; Park, C.-W. In *Visual testing system for the damaged area detection of wind power plant blade*, IEEE ISR 2013, 2013; IEEE: pp 1-5.
45. Yu, Y.; Cao, H.; Yan, X.; Wang, T.; Ge, S.S. Defect identification of wind turbine blades based on defect semantic features with transfer feature extractor. *Neurocomputing* **2020**, *376*, 1-9.
46. Poozesh, P.; Baqersad, J.; Niezrecki, C.; Avitabile, P.; Harvey, E.; Yarala, R. Large-area photogrammetry based testing of wind turbine blades. *Mechanical Systems and Signal Processing* **2017**, *86*, 98-115.
47. Márquez, F.P.G.; Ramírez, I.S. Condition monitoring system for solar power plants with radiometric and thermographic sensors embedded in unmanned aerial vehicles. *Measurement* **2019**, *139*, 152-162.
48. Khadka, A.; Fick, B.; Afshar, A.; Tavakoli, M.; Baqersad, J. Non-contact vibration monitoring of rotating wind turbines using a semi-autonomous uav. *Mechanical Systems and Signal Processing* **2020**, *138*, 106446.
49. Wang, L.; Zhang, Z. Automatic detection of wind turbine blade surface cracks based on uav-taken images. *IEEE Transactions on Industrial Electronics* **2017**, *64*, 7293-7303.
50. Zhang, D.; Burnham, K.; Mcdonald, L.; Macleod, C.; Dobie, G.; Summan, R.; Pierce, G. In *Remote inspection of wind turbine blades using uav with photogrammetry payload*, 56th Annual British Conference of Non-Destructive Testing-NDT 2017, 2017.
51. Muñoz, C.Q.G.; Jiménez, A.A.; Márquez, F.P.G. Wavelet transforms and pattern recognition on ultrasonic guides waves for frozen surface state diagnosis. *Renewable Energy* **2018**, *116*, 42-54.
52. Gómez Muñoz, C.Q.; García Marquez, F.P.; Hernandez Crespo, B.; Makaya, K. Structural health monitoring for delamination detection and location in wind turbine blades employing guided waves. *Wind Energy* **2019**, *22*, 698-711.
53. Arcos Jiménez, A.; Gómez Muñoz, C.Q.; García Márquez, F.P. Machine learning for wind turbine blades maintenance management. *Energies* **2018**, *11*, 13.
54. Garcia Marquez, F.P.; Gomez Munoz, C.Q. A new approach for fault detection, location and diagnosis by ultrasonic testing. *Energies* **2020**, *13*, 1192.
55. Tiwari, K.A.; Raisutis, R. Refinement of defect detection in the contact and non-contact ultrasonic non-destructive testing of wind turbine blade using guided waves. *Procedia Structural Integrity* **2018**, *13*, 1566-1570.
56. Yang, K.; Rongong, J.A.; Worden, K. Damage detection in a laboratory wind turbine blade using techniques of ultrasonic ndt and shm. *Strain* **2018**, *54*, e12290.
57. Liu, Q.; Wang, Z.; Long, S.; Cai, M.; Wang, X.; Chen, X.; Bu, J. In *Research on automatic positioning system of ultrasonic testing of wind turbine blade flaws*, IOP Conference Series: Earth and Environmental Science, 2017; IOP Publishing: p 012074.
58. Li, X.; Sun, J.; Shen, J.; Wang, X.; Zhang, C.; Zhao, Y. In *Adhesive quality inspection of wind rotor blades using thermography*, AIP Conference Proceedings, 2018; AIP Publishing: p 230020.
59. Park, B.; Sohn, H.; Malinowski, P.; Ostachowicz, W. Delamination localization in wind turbine blades based on adaptive time-of-flight analysis of noncontact laser ultrasonic signals. *Nondestructive Testing and Evaluation* **2017**, *32*, 1-20.

60. Moll, J.; Arnold, P.; Mälzer, M.; Krozer, V.; Pozdniakov, D.; Salman, R.; Rediske, S.; Scholz, M.; Friedmann, H.; Nuber, A. Radar-based structural health monitoring of wind turbine blades: The case of damage detection. *Structural Health Monitoring* **2018**, *17*, 815-822.
61. Larrañaga-Valsero, B.; Smith, R.A.; Tayong, R.B.; Fernández-López, A.; Güemes, A. Wrinkle measurement in glass-carbon hybrid laminates comparing ultrasonic techniques: A case study. *Composites Part A: Applied Science and Manufacturing* **2018**, *114*, 225-240.
62. Tiwari, K.A.; Raisutis, R.; Samaitis, V. Signal processing methods to improve the signal-to-noise ratio (snr) in ultrasonic non-destructive testing of wind turbine blade. *Procedia Structural Integrity* **2017**, *5*, 1184-1191.
63. Tiwari, K.A.; Raisutis, R. Post-processing of ultrasonic signals for the analysis of defects in wind turbine blade using guided waves. *The Journal of Strain Analysis for Engineering Design* **2018**, 0309324718772668.
64. Tiwari, K.A.; Raisutis, R.; Samaitis, V. Hybrid signal processing technique to improve the defect estimation in ultrasonic non-destructive testing of composite structures. *Sensors* **2017**, *17*, 2858.
65. Arcos Jiménez, A.; Gómez Muñoz, C.Q.; García Márquez, F.P. Dirt and mud detection and diagnosis on a wind turbine blade employing guided waves and supervised learning classifiers. *Reliability Engineering & System Safety* **2018**.
66. Jiménez, A.A.; Márquez, F.P.G.; Moraleda, V.B.; Muñoz, C.Q.G. Linear and nonlinear features and machine learning for wind turbine blade ice detection and diagnosis. *Renewable energy* **2019**, *132*, 1034-1048.
67. Brett, C.; Gunn, D.; Dashwood, B.; Holyoake, S.; Wilkinson, P. Development of a technique for inspecting the foundations of offshore wind turbines. *Insight-Non-Destructive Testing and Condition Monitoring* **2018**, *60*, 19-27.
68. de la Hermosa González, R.R.; Márquez, F.P.G.; Dimlaye, V. Maintenance management of wind turbines structures via mfcs and wavelet transforms. *Renewable and Sustainable Energy Reviews* **2015**, *48*, 472-482.
69. Lamarre, A. In *Improved inspection of composite wind turbine blades with accessible advanced ultrasonic phased array technology*, 15th Asia Pacific Conference for Non-Destructive Testing (APCNDT2017), Singapore, 2017; pp 1-8.
70. Li, T.; Yang, Y.; Gu, X.-W.; Long, S.-G.; Wang, Z.-h. Quantitative research into millimetre-scale debonding defects in wind turbine blade bonding structures using ultrasonic inspection: Numerical simulations. *Insight-Non-Destructive Testing and Condition Monitoring* **2019**, *61*, 316-323.
71. Ren, Y.; Qu, F.; Liu, J.; Feng, J.; Li, X. In *A universal modeling approach for wind turbine condition monitoring based on scada data*, 2017 6th Data Driven Control and Learning Systems (DDCLS), 26-27 May 2017, 2017; pp 265-269.
72. Doroshtnasir, M.; Worzewski, T.; Krankenhagen, R.; Röllig, M. On‐site inspection of potential defects in wind turbine rotor blades with thermography. *Wind Energy* **2016**, *19*, 1407-1422.
73. Ramirez, I.S.; Muñoz, C.Q.G.; Marquez, F.P.G. In *A condition monitoring system for blades of wind turbine maintenance management*, Proceedings of the tenth international conference on management science and engineering management, 2017; Springer: pp 3-11.
74. Avdelidis, N.P.; Gan, T.H. 24 - non-destructive evaluation (nde) of composites: Infrared (ir) thermography of wind turbine blades. In *Non-destructive evaluation (nde) of polymer matrix composites*, Karbhari, V.M., Ed. Woodhead Publishing: 2013; pp 634-650e.

75. Worzewski, T.; Krankenhagen, R.; Doroshtnasir, M.; Röllig, M.; Maierhofer, C.; Steinfurth, H. Thermographic inspection of a wind turbine rotor blade segment utilizing natural conditions as excitation source, part i: Solar excitation for detecting deep structures in gfrp. *Infrared Physics & Technology* **2016**, *76*, 756-766.
76. Lizaranzu, M.; Lario, A.; Chiminelli, A.; Amenabar, I. Non-destructive testing of composite materials by means of active thermography-based tools. *Infrared Physics & Technology* **2015**, *71*, 113-120.
77. Hwang, S.; An, Y.-K.; Sohn, H. Continuous line laser thermography for damage imaging of rotating wind turbine blades. *Procedia Engineering* **2017**, *188*, 225-232.
78. Hwang, S.; An, Y.-K.; Yang, J.; Sohn, H. Remote inspection of internal delamination in wind turbine blades using continuous line laser scanning thermography. *International Journal of Precision Engineering and Manufacturing-Green Technology* **2020**, 1-14.
79. Dollinger, C.; Sorg, M.; Balaresque, N.; Fischer, A. Measurement uncertainty of ir thermographic flow visualization measurements for transition detection on wind turbines in operation. *Experimental Thermal and Fluid Science* **2018**, *97*, 279-289.
80. Dollinger, C.; Balaresque, N.; Gaudern, N.; Gleichauf, D.; Sorg, M.; Fischer, A. Ir thermographic flow visualization for the quantification of boundary layer flow disturbances due to the leading edge condition. *Renewable Energy* **2019**, *138*, 709-721.
81. Martin, R.W.; Sabato, A.; Schoenberg, A.; Giles, R.H.; Niezrecki, C. Comparison of nondestructive testing techniques for the inspection of wind turbine blades' spar caps. *Wind Energy* **2018**.
82. Worzewski, T.; Krankenhagen, R.; Doroshtnasir, M. Thermographic inspection of wind turbine rotor blade segment utilizing natural conditions as excitation source, part ii: The effect of climatic conditions on thermographic inspections–a long term outdoor experiment. *Infrared Physics & Technology* **2016**, *76*, 767-776.
83. Taraghi, I.; Lopato, P.; Paszkiewicz, S.; Piesowicz, E. X-ray and terahertz imaging as non-destructive techniques for defects detection in nanocomposites foam-core sandwich panels containing carbon nanotubes. *Polymer Testing* **2019**, *79*, 106084.
84. Garcea, S.C.; Wang, Y.; Withers, P.J. X-ray computed tomography of polymer composites. *Composites Science and Technology* **2018**, *156*, 305-319.
85. Chen, X. Fractographic analysis of sandwich panels in a composite wind turbine blade using optical microscopy and x-ray computed tomography. *Engineering Failure Analysis* **2020**, *111*, 104475.
86. Reid, A.; Martinez, I.; Marshall, M.; Minniti, T.; Kabra, S.; Kockelmann, W.; Connolley, T.; Mostafavi, M. Mapping of axial plastic zone for roller bearing overloads using neutron transmission imaging. *Materials & Design* **2018**, *156*, 103-112.
87. Emerson, M.J.; Jespersen, K.M.; Dahl, A.B.; Conradsen, K.; Mikkelsen, L.P. Individual fibre segmentation from 3d x-ray computed tomography for characterising the fibre orientation in unidirectional composite materials. *Composites Part A: Applied Science and Manufacturing* **2017**, *97*, 83-92.
88. Fantidis, J.; Potolias, C.; Bandekas, D. Wind turbine blade nondestructive testing with a transportable radiography system. *Science and Technology of Nuclear Installations* **2011**, *2011*.
89. Jasinien, E.; Raiutis, R.; Voleiis, A.; Vladiauskas, A.; Mitchard, D.; Amos, M. Ndt of wind turbine blades using adapted ultrasonic and radiographic techniques. *Insight-Non-Destructive Testing and Condition Monitoring* **2009**, *51*, 477-483.
90. Mikkelsen, L.P. In *Visualizing composite materials for wind turbine blades using x-ray tomography*, Materials for Tomorrow 2019: Visualizing Materials, 2019.

91. Moll, J. In *Numerical and experimental analysis of defect detection in jointed electromagnetic waveguides*, 2019 13th European Conference on Antennas and Propagation (EuCAP), 2019; IEEE: pp 1-4.
92. Li, Z.; Haigh, A.; Soutis, C.; Gibson, A.; Sloan, R. Microwaves sensor for wind turbine blade inspection. *Applied Composite Materials* **2017**, *24*, 495-512.
93. Zhao, Q.; Zhang, K.; Xu, H.; Avila, J.R.S.; Zhao, L.; Wang, M.; Han, Y.; Zhang, Z.; Yin, W. In *Measurement of cfrp surface crack based on electromagnetic measuring system*, 2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 2019; IEEE: pp 1-5.
94. Im, K.-H.; Kim, S.-K.; Jung, J.-A.; Cho, Y.-T.; Wood, Y.-D.; Chiou, C.-P. Nde characterization and inspection techniques of trailing edges in wind turbine blades using terahertz waves. *Journal of Mechanical Science and Technology* **2019**, *33*, 4745-4753.
95. Zhong, S. Progress in terahertz nondestructive testing: A review. *Frontiers of Mechanical Engineering* **2019**, 1-9.
96. Moll, J.; Simon, J.; Malzer, M.; Krozer, V.; Pozdniakov, D.; Salman, R.; Durr, M.; Feulner, M.; Nuber, A.; Friedmann, H. Radar imaging system for in-service wind turbine blades inspections: Initial results from a field installation at a 2 mw wind turbine. *Progress In Electromagnetics Research* **2018**, *162*, 51-60.
97. Teng, W.; Ding, X.; Zhang, Y.; Liu, Y.; Ma, Z.; Kusiak, A. Application of cyclic coherence function to bearing fault detection in a wind turbine generator under electromagnetic vibration. *Mechanical Systems and Signal Processing* **2017**, *87*, 279-293.
98. Esmaeili, K.; Zuercher, M.; Wang, L.; Harvey, T.; Holweger, W.; White, N.; Schlücker, E. Advanced signal processing techniques for wind turbine gearbox bearing failure detection. **2017**.
99. Leaman, F.; Hinderer, S.; Baltes, R.; Clausen, E.; Rieckhoff, B.; Schelenz, R.; Jacobs, G. Acoustic emission source localization in ring gears from wind turbine planetary gearboxes. *Forschung im Ingenieurwesen* **2019**, *83*, 43-52.
100. Crivelli, D.; Hutt, S.; Clarke, A.; Borghesani, P.; Peng, Z.; Randall, R. Condition monitoring of rotating machinery with acoustic emission: A british–australian collaboration. In *Asset intelligence through integration and interoperability and contemporary vibration engineering technologies*, Springer: 2019; pp 119-128.
101. Kim, G.; Seo, M.-K.; Choi, N.; Kim, Y.-I.; Kim, K.-B. Comparison of pzt, pzt based 1–3 composite and pmn–pt acoustic emission sensors for glass fiber reinforced plastics. *International Journal of Precision Engineering and Manufacturing* **2019**, *20*, 1007-1015.
102. Tang, J.; Soua, S.; Mares, C.; Gan, T.-H. An experimental study of acoustic emission methodology for in service condition monitoring of wind turbine blades. *Renewable Energy* **2016**, *99*, 170-179.
103. Saeedifar, M.; Najafabadi, M.A.; Yousefi, J.; Mohammadi, R.; Toudeshky, H.H.; Minak, G. Delamination analysis in composite laminates by means of acoustic emission and bi-linear/tri-linear cohesive zone modeling. *Composite Structures* **2017**, *161*, 505-512.
104. Gómez, C.; García, F.; Arcos, A.; Cheng, L.; Kogia, M.; Mohimi, A.; Papaelias, M. A heuristic method for detecting and locating faults employing electromagnetic acoustic transducers. *Eksploatacja i Niezawodność* **2017**, *19*.
105. Angelopoulos, N.; Papaelias, M. Automatic statistical analysis of acoustic emission data sets. In *Non-destructive testing and condition monitoring techniques for renewable energy industrial assets*, Elsevier: 2020; pp 159-176.
106. Tang, J.; Soua, S.; Mares, C.; Gan, T.-H. A pattern recognition approach to acoustic emission data originating from fatigue of wind turbine blades. *Sensors* **2017**, *17*, 2507.

107. Xu, D.; Liu, P.; Chen, Z.; Leng, J.; Jiao, L. Achieving robust damage mode identification of adhesive composite joints for wind turbine blade using acoustic emission and machine learning. *Composite Structures* **2020**, *236*, 111840.
108. Liu, P.; Xu, D.; Li, J.; Chen, Z.; Wang, S.; Leng, J.; Zhu, R.; Jiao, L.; Liu, W.; Li, Z. Damage mode identification of composite wind turbine blade under accelerated fatigue loads using acoustic emission and machine learning. *Structural Health Monitoring* **2019**, 1475921719878259.
109. Wang, Y.; Zhang, Y.; Yang, G.; Zhang, R. In *Identification of engine foreign object impact based on acoustic emission and radical basis function neural network*, 2019 IEEE 2nd International Conference on Electronic Information and Communication Technology (ICEICT), 2019; IEEE: pp 291-296.
110. Doliński, Ł.; Krawczuk, M.; Żak, A. In *Damage detection in the wind turbine blade using root mean square and experimental modal parameters*, Proceedings of the 13th International Conference on Damage Assessment of Structures, 2020; Springer: pp 728-742.
111. Liu, Z.; Wang, X.; Zhang, L. Fault diagnosis of industrial wind turbine blade bearing using acoustic emission analysis. *IEEE Transactions on Instrumentation and Measurement* **2020**.
112. Fuentes, R.; Dwyer-Joyce, R.; Marshall, M.; Wheals, J.; Cross, E. Detection of sub-surface damage in wind turbine bearings using acoustic emissions and probabilistic modelling. *Renewable Energy* **2020**, *147*, 776-797.
113. Marks, R.; Gillam, C.; Clarke, A.; Armstrong, J.; Pullin, R. Damage detection in a composite wind turbine blade using 3d scanning laser vibrometry. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **2017**, *231*, 3024-3041.
114. Wilkinson, P.; Gunn, D.; Holyoake, S.; Dashwood, B.; Brett, C.; Rees, J. Low frequency acoustic and ultrasound waves to characterise layered media. *NDT & E International* **2018**, *96*, 35-46.
115. Poozesh, P.; Aizawa, K.; Niezrecki, C.; Baqersad, J.; Inalpolat, M.; Heilmann, G. Structural health monitoring of wind turbine blades using acoustic microphone array. *Structural Health Monitoring* **2017**, *16*, 471-485.
116. Beganovic, N.; Söffker, D. Structural health management utilization for lifetime prognosis and advanced control strategy deployment of wind turbines: An overview and outlook concerning actual methods, tools, and obtained results. *Renewable and Sustainable Energy Reviews* **2016**, *64*, 68-83.
117. Francis, D. 4 - non-destructive evaluation (nde) of composites: Introduction to shearography. In *Non-destructive evaluation (nde) of polymer matrix composites*, Karbhari, V.M., Ed. Woodhead Publishing: 2013; pp 56-83.
118. Zhao, Q.; Dan, X.; Sun, F.; Wang, Y.; Wu, S.; Yang, L. Digital shearography for ndt: Phase measurement technique and recent developments. *Applied Sciences* **2018**, *8*, 2662.
119. Macedo, F.J.; Benedet, M.E.; Fantin, A.V.; Willemann, D.P.; da Silva, F.A.A.; Albertazzi, A. Inspection of defects of composite materials in inner cylindrical surfaces using endoscopic shearography. *Optics and Lasers in Engineering* **2018**, *104*, 100-108.
120. Ye, Y.; Ma, K.; Zhou, H.; Arola, D.; Zhang, D. An automated shearography system for cylindrical surface inspection. *Measurement* **2019**, *135*, 400-405.
121. Liu, L.; Guo, C.; Wang, L.; Mei, H. In *Non-destructive testing method for composite insulators based on digital shearography*, The International Symposium on High Voltage Engineering, 2019; Springer: pp 862-870.
122. TANG, J.-f.; WANG, Y. Nondestructive testing of composites based on shearography. *Journal of Nanjing University of Aeronautics & Astronautics* **2005**, *1*.

123. Amenabar, I.; Mendikute, A.; López-Arraiza, A.; Lizaranzu, M.; Aurrekoetxea, J. Comparison and analysis of non-destructive testing techniques suitable for delamination inspection in wind turbine blades. *Composites Part B: Engineering* **2011**, *42*, 1298-1305.
124. Mikkelsen, L.P. In *Observations of microscale tensile fatigue damage mechanisms of composite materials for wind turbine blades*, IOP Conference Series: Materials Science and Engineering, 2018; IOP Publishing: p 012006.
125. Maierhofer, C.; Röllig, M.; Gower, M.; Lodeiro, M.; Baker, G.; Monte, C.; Adibekyan, A.; Gutschwager, B.; Knazowicka, L.; Blahut, A. Evaluation of different techniques of active thermography for quantification of artificial defects in fiber-reinforced composites using thermal and phase contrast data analysis. *International Journal of Thermophysics* **2018**, *39*, 61.
126. Strugała, G.; Klugmann, M.; Landowski, M.; Szkodo, M.; Mikielewicz, D. A universal ndt method for examination of low energy impact damage in cfrp with the use of tlc film. *Nondestructive Testing and Evaluation* **2018**, 1-14.
127. Rizk, P.; Al Saleh, N.; Younes, R.; Ilinca, A.; Khoder, J. Hyperspectral imaging applied for the detection of wind turbine blade damage and icing. *Remote Sensing Applications: Society and Environment* **2020**, 100291.
128. Baqersad, J.; Poozesh, P.; Niezrecki, C.; Avitabile, P. Photogrammetry and optical methods in structural dynamics–a review. *Mechanical Systems and Signal Processing* **2017**, *86*, 17-34.
129. Iliopoulos, A.N.; Van Hemelrijck, D.; Vlassenbroeck, J.; Aggelis, D.G. Assessment of grouted samples from monopile wind turbine foundations using combined non-destructive techniques. *Construction and Building Materials* **2016**, *122*, 855-862.
130. García Márquez, F.P.; Segovia Ramírez, I.; Mohammadi-Ivatloo, B.; Marugán, A.P. Reliability dynamic analysis by fault trees and binary decision diagrams. *Information* **2020**, *11*, 324.