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Non-Contact Inspection Methods for Wind Turbine Blade Maintenance: Techno–Economic Review of Techniques for Integration with Industry 4.0

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Abstract

Wind energy has emerged as a critical source of renewable energy worldwide, and the performance of wind turbines relies heavily on the quality and design of their blades. However, the manual manufacturing process of wind turbine blades using polymeric matrix composite materials makes them susceptible to irregular and complex loading damage. This damage can lead to reduced power generation, shortened lifespan, and increased maintenance costs. Therefore, non-destructive testing (NDT) of wind turbine blades is necessary to identify surface and internal defects, ensuring the sustainable operation of the wind turbines. This article briefly reviews wind turbine blades' materials, design, and manufacturing methodology. We also discuss the inspection strategy during production and inspection methods during operation. Five non-contact NDT techniques, including thermography, radiography, machine vision, laser shearography testing, and microwave testing, are appraised to inspect wind turbine blade damage. These techniques were evaluated using a Techno–Economic approach that considers technical and economic factors, such as accuracy, cost, reliability, and ease of implementation. Thanks to technological advancements, integrating non-contact inspection methods with Industry 4.0 technologies can help improve wind power generation's safety, efficiency, and reliability. However, evaluating available methods' compatibility with Industry 4.0 technologies may be necessary.

Keywords Wind turbine blade (WTB) · Non-contact inspection · Damage detection · Techno–economic modeling

1 Introduction

Renewable and clean energy resources, such as wind turbines, have gained global attention due to their potential to mitigate environmental impacts. Given the high construction and maintenance costs, ensuring the health of sensitive and critical wind farm parts is crucial. In offshore wind turbine blades (WTB), operation and maintenance (O&M) account for 15–35% of the total costs [1]. Wind energy has been booming for over a decade and accounts for a significant share of the global energy market [2]. According to the Global Wind Energy Council's (GWEC) report in 2021, there is a total capacity of 743 GW of wind turbines installed worldwide. In 2020 alone, there were 93 GW of new installations, with 86.9 GW of turbines installed on land (onshore) and 6.1 GW installed at sea (offshore). Given the significant growth of the wind energy industry and the high costs associated with operating and maintaining wind turbines, it is important to ensure that these turbines are optimally functioning

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under various conditions and in different geographic locations. These turbines must operate under a wide range of conditions, including exposure to saltwater, sand particles, insects, lightning, ultraviolet rays, and ice formation [3].

Due to the high wind potential, wind turbines are increasingly used in northern regions. However, the harsh environmental conditions in these areas can cause significant wear and tear on the turbines. As a result, technology must adapt to the harsh climatic conditions in certain locations, such as extreme temperatures and icing. Icing, which refers to the accumulation of ice on the blades of wind turbines, can complicate the operation and maintenance of these turbines in these areas [4]. As ice builds up on the blades and other components of the turbine, it can cause reduced efficiency, increased wear and tear, and even complete failure in extreme cases. Therefore, mitigating ice buildup is critical in designing, operating, and maintaining wind turbines in cold-weather environments [5]. This ice buildup on the blades increases the stress on the blades and causes significant vibrations that lead to material fatigue and can also cause damage [6]. Hence, regular maintenance and inspection are necessary to detect any issues early on and avoid costly repairs or replacements [7].

Despite the challenges posed by harsh weather conditions, wind farm operators are determined to overcome them rather than avoid these areas altogether. This is because some of the world's greatest wind potential is found in these regions [8]. The materials used in northern environments for the blades can become brittle in very low temperatures, resulting in cracks or damage. However, wind turbine manufacturers can now offer solutions to these extreme temperature constraints in designing, manufacturing, operating, and maintaining wind turbines. This allows wind farm operators to mitigate the effects of extreme temperatures on the turbines, ensuring they continue to function effectively in harsh environments [9, 10]. The efficient operation of wind turbines in northern climates requires careful consideration of blade material selection, appropriate design and manufacturing adapted to extreme winter conditions, and the ability to withstand the additional load caused by ice accumulation on the blades. Regular inspections are also necessary to ensure the blades remain in good condition and to promptly detect any cracks or failures, allowing for timely repairs and ensuring optimal turbine performance and estimated energy production.

For instance, Canada, one of the world's coldest countries, also boasts the highest wind energy potential. To harness this potential, wind farm operators in Canada have implemented best practices for operating wind turbines in cold weather, including the use of specialized materials and regular maintenance and inspections [8, 11]. Ontario, Quebec, and Alberta are the provinces with the highest wind energy production in Canada. According to the Canadian Wind Energy

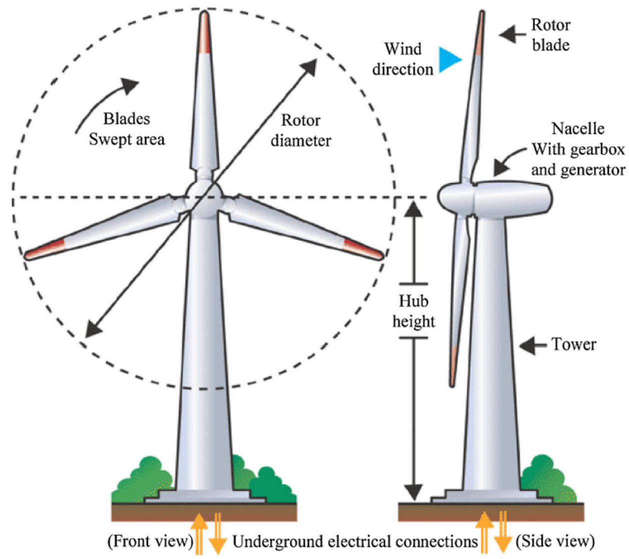

Fig. 1 Wind energy system schematic [14]

Association (CanWEA), the country's total installed wind energy capacity is 12,239 MW, which is comprised of 6,409 wind turbines and 19,227 blades that require regular inspections and maintenance. Ontario has 2,515 installed wind turbines, which translates to 7,545 blades requiring inspection and maintenance services. Quebec has 1,879 installed turbines, which require 5,637 blades to be serviced. Alberta has 901 installed turbines, and requires 2,703 blades to be inspected and maintained regularly [12]. According to the Government of Quebec [13], the province of Quebec had 3,879 MW of wind power capacity in 2020 (i.e. 1935 turbines integrated to the Hydro-Quebec grid) and is expected to have 3,933 MW of wind power by 2022. Therefore, a large number of wind turbines have been installed and operated in harsh climatic conditions (i.e. icing and very low temperatures), whose inspection is of high importance during winter periods when consumption of electricity rises and surplus production is anticipated. Similar issues are likely to exist in northern Europe, where wind energy production is high and cold weather conditions are common. Countries such as Denmark, Germany, and Sweden have invested heavily in wind energy and adopted best practices for operating wind turbines in cold weather. It is necessary to use specialized materials to withstand harsh weather conditions such as frost and low temperature. Figure 1 illustrates main design characteristics of wind turbine structure.

As wind turbine development expands, reliable inspection methods capable of detecting defects with high precision are increasingly important. Non-destructive inspections (NDI) involve the permanent and automatic inspection of defects, stresses, strains, and condition indicators. The wind turbine blade (WTB) is a critical component of wind turbines, and failure may result in catastrophic structural failures [15]. The harsh environments in which wind turbines operate, coupled with improper design, stress concentration, and poor surface finish, can create defects and grow inherent imperfections in wind turbine blades (WTBs). To address these issues, nondestructive inspection, testing, and evaluation techniques are used to examine and analyze materials and structures without causing damage to them. Structural health monitoring (SHM) is a process that uses these techniques to continuously monitor the condition of structures and detect any damage or defects. NDE 4.0 is an advanced form of NDE that combines the power of the internet of things (IoT), big data analytics, and machine learning (ML) algorithms to enhance the accuracy and speed of inspections. NDE 4.0 is becoming increasingly close to SHM as it allows for real-time data collection and analysis, enabling early detection of potential issues and facilitating predictive maintenance. NDT is a commonly used option to inspect various types of anomalies in WTBs [16]. NDT methods are commonly used in regular inspection programs, particularly for critical parts and components not requiring disassembly to provide adequate access during testing, however, NDT can be conducted during equipment downtime or disassembly. Therefore, there is an increasing demand for NDT techniques that inspect parts in operating conditions. SHM can be applied in industries that cannot tolerate long downtimes or for components that are difficult to access. However, this method might be unsuitable for wide-ranging evaluations. In the following section, we will review wind turbine blades' materials and manufacturing methodologies.

2 Material and Manufacturing Process of Wind Turbine

Wind turbines are complex structures with several components, each with its unique material composition. Steel is the most common material in wind turbines in various parts including the tower, hub, and foundation, comprising 66–79% of the total mass. Fiberglass, resin, and plastic comprise 11–26% of the turbine's total mass, while cast iron and copper contribute 5–17% and 1%, respectively. Aluminum is the least used material, accounting for only 0–2%. Hence, wind turbines are complex machines whose rotor blades are among their most critical components. In addition to rotor blades, gearboxes are also critical components of a wind turbine since thses parts operate under extreme loads, making them an integral part of regular maintenance and inspection.

Hence, the selection of materials and the design of wind turbines can significantly impact the performance and efficiency of wind turbines. The design of the blade affects its ability to extract energy from the wind, as well as its ability to withstand the loads it experiences during operation. The materials selection and design process must meet stringent

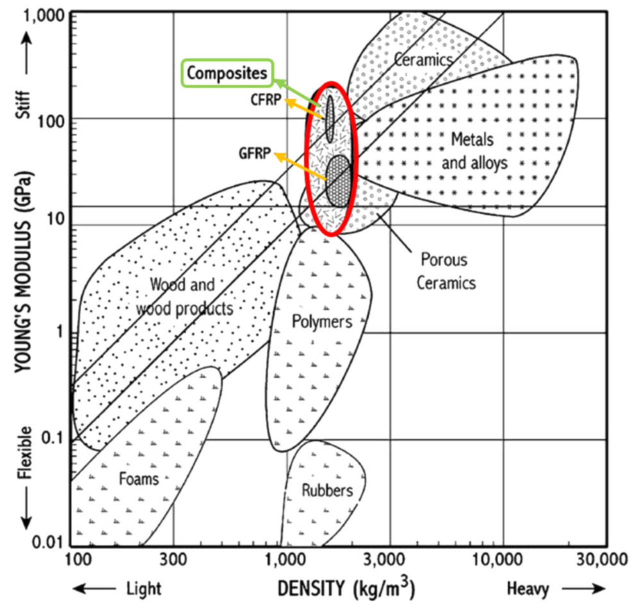

Fig. 2 Diagram of stiffness versus density for materials [18]

performance and economic requirements, focusing on stiffness, density, and long-term fatigue. A wind turbine rotor blade is designed similarly to a beam in terms of mechanical design. As the blade rotates, it experiences various loads, including gravitational and aerodynamic forces. To maintain optimal aerodynamic performance, high-stiffness materials must be used. Additionally, low-density materials can effectively reduce the gravitational forces that act on the blade, increasing the system's efficiency. Finally, long fatigue life is essential to reduce material degradation over time. Optimizing these aspects simultaneously can be challenging. The material property requirements of high stiffness, low weight, and long fatigue life can be evaluated using property combination diagrams. Figure 2 shows the stiffness versus density to be used for materials selection. The merit index for a beam, $Mb = E1/2/\rho$, is represented by sloping lines with Mb equal to 0.003 (lower line) and 0.006 (upper line) [17]. As shown in the figure, GFRP and CFRP composites deliver the best range of properties within the merit index span for wind structures. However, it is essential to consider all factors, such as cost, availability, and performance, when selecting materials and designing rotor blades. Other factors, such as manufacturing processes, material properties, and design considerations, must also be taken into account. For example, the production of large wind turbine rotor blades can be challenging due to their size and the complex shapes they require. This complexity can increase the cost of production and limit the available materials for use in the blade design. Therefore, it is essential to consider all factors when designing and selecting materials for wind turbine rotor blades.

In the early years of wind energy development in modern era, wind turbine blades were manufactured using wet-hand lay-up technology in open molds. The fiberglass reinforcement was impregnated using brushes and rollers, and the shells were bonded together or to the spars using adhesives. This technology was primarily used for the production of small and medium-sized blades. The same technology was employed for larger blades, but with the addition of a web inserted between the two sides, bonded together using adhesives, and plies with a higher fiber content. However, this manufacturing process had disadvantages, including high labor costs, relatively low product quality, and environmental concerns. Filament winding technology was introduced to overcome these limitations, which offered the possibility of improving turbine quality and reducing labor costs. Filament winding involves the application of continuous fibers to a rotating mandrel to create a strong, lightweight structure. The resulting composite structure is made up of a series of circumferential layers that are wound over the length of the mandrel. The fibers are impregnated with resin as they are applied, resulting in a high-quality product with consistent properties. Filament winding technology also allows for the creation of complex shapes and contours, making it an ideal manufacturing method for wind turbine blades [19]. The development of vacuum infusion and prepreg technology has greatly improved the production of wind turbine blades by providing a cost-effective, efficient, and environmentally friendly manufacturing method that meets the performance and economic requirements of the industry [20]. Prepreg technology involves the impregnation of fibers with a matrix material prior to their use in the manufacturing process. The matrix material is already incorporated into the pre-impregnated composite fibers, allowing for greater control over the composite properties and reducing the risk of voids or other defects in the final product. This technology was originally developed for the aerospace industry, where high performance and precision are essential. Prepreg materials can be formed into complex shapes and used for various industrial applications, including wind turbine blades. One of the key advantages of prepreg technology is its ability to reduce manufacturing time and costs compared to traditional wet lay-up methods. It also produces a higher quality and more consistent product. However, the use of prepreg materials requires specialized equipment and facilities, and the material can be more expensive than traditional composites. The resin infusion process is widely used in the production of wind blades, especially for long blades. The fibers are first placed in a closed and sealed mold to create a fiber composite product. The mold is then infused with resin and injected into the cavity. After the component has cured, heat is applied to complete the process. There are two variants of resin infusion methods: vacuum-assisted resin transfer molding (VARTM) and resin transfer molding (RTM). RTM uses high atmospheric pressure for resin injection, while VARTM uses a vacuum or pressure lower than atmospheric pressure [21]. As blade length varies, a VARTM mold part is constructed of dry fiber fabrics sandwiched between polymer foam and balsa wood. A laminate is formed by a series of plies that run from the root to the tip, forming a thicker laminate at the root and a thinner laminate at the tip. After vacuum injection and curing, the composite structure may be post-cured at high temperature in some cases. This fabrication method is primarily suitable for upscaling due to its high number of resin inlets and vacuum suction points [22].

The high cost and time involved in blade manufacturing make it difficult to discard them when they become defective. Therefore, it is preferable to select more damage-tolerant materials, allowing for larger manufacturing defects to be tolerated. Environmentally friendly technologies allow for greater control over the properties of materials and a greater volume of fibers to be produced. Automation will eventually be used to lay up the tape, place the fibers, and create two-piece or segment wind blades to improve quality and reduce costs [20]. Compared to aerospace, wind turbine blades require significantly larger and thicker composite structures, which poses a challenge for automation. However, researchers have found that certain blade parts can be made from 3D woven composites instead of traditional fiber-reinforced laminates. By utilizing advanced composite materials and manufacturing techniques, wind turbine blades can be made more efficient, leading to increased energy production and reduced costs [23]. Sandwich constructions, consisting of multiaxial composite laminates for the outer shell and for the shear webs in the blades are shown in Fig. 3.

2.1 Inspection Strategy for Blade Manufacturing

The manual manufacturing process of blades can hinder the development of stronger and more reliable wind turbines. However, advancements have been made in blade manufacturing systems to facilitate the process and improve the product's final quality. One of the areas of focus for manufacturers is automating the manufacturing process to reduce cycle time, increase accuracy and repeatability, and reduce costs. Utilizing high-performance composite materials with the support of strategic suppliers is critical to developing more robust and reliable blades. Employing an advanced tooling system to manufacture ultra-precision molding and assembly systems is another area of focus for blade manufacturers. Manufacturers can produce blades with complex geometries and internal aerodynamic properties with advanced tooling, resulting in significant energy production. To ensure the accuracy and quality of the blades, manufacturers can use advanced metrology, inspection, testing, and quality assurance tools to validate and verify the

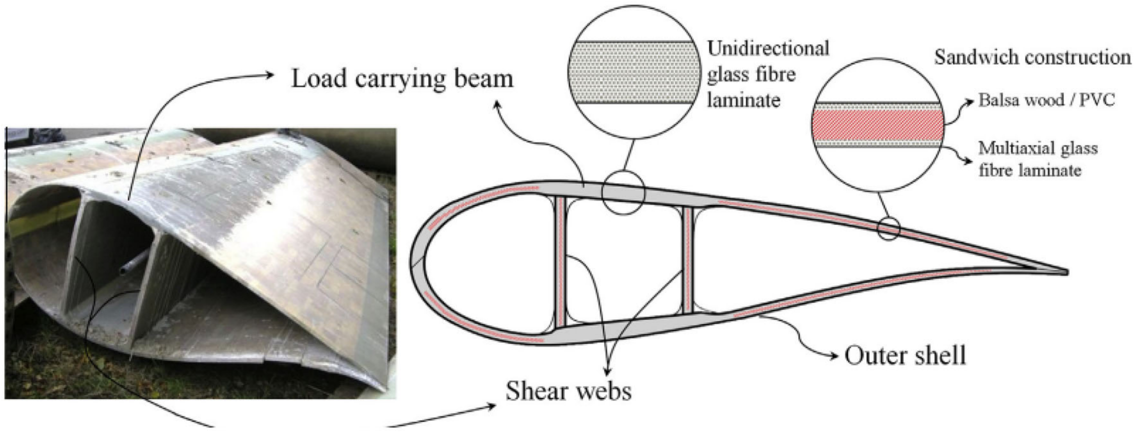

Fig. 3 Wind turbine blade structure and material [24]

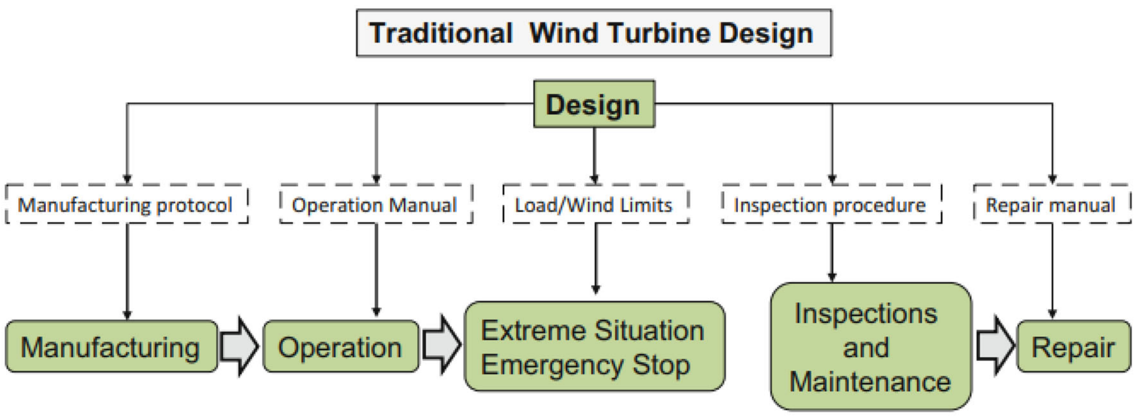

Fig. 4 Inspection strategy in the manufacturing process [25]

accuracy and quality of the blades, ensuring that they meet the required specifications. Additionally, using robots to perform various finishing processes can protect the blade from adverse weather conditions, making the material less susceptible to defects caused by erosion and mechanical bending, increasing its durability. Robots can traverse the entire blade in a single non-stop movement, improving the final finish and making the inspection process safer for workers. Advancements in blade manufacturing systems have made it possible to develop stronger wind turbine blades. The inspection strategy is a key element in ensuring the success of production objectives within a specified timeline. It is influenced by various factors such as production planning, industry needs, process planning, and manufacturing capacity. The success of an inspection strategy depends on the available technological capabilities and resources. Therefore, the inspection strategy must be designed according to the factory's productive capacity, processing equipment, and manufacturing process limitations. Process planning is crucial in developing an inspection strategy, as it involves determining the details of production and assembly operations based on capacities and design. Industries are constantly seeking to optimize their processes and mechanisms to increase quality and customer satisfaction while expanding their technological and productive capabilities. To achieve these objectives, long-term strategic plans must be developed to increase production capacity and profitability. It is important to note that a well-designed inspection strategy relies on effectively integrating quality control measures throughout the manufacturing process. Inspection of raw materials, production processes, and intermediate products is just as important as the inspection of the final product. This ensures that any defects or issues are identified and addressed in a timely manner, reducing the likelihood of production delays and improving overall quality. Effective inspection strategies provide a competitive advantage in the industry. They ensure that production objectives are achieved within the specified timeline, customer satisfaction is maintained, and profitability is increased. Manufacturers must, therefore, invest in developing and executing a comprehensive inspection strategy that incorporates quality control measures throughout the manufacturing process. By doing so, they can achieve a high level

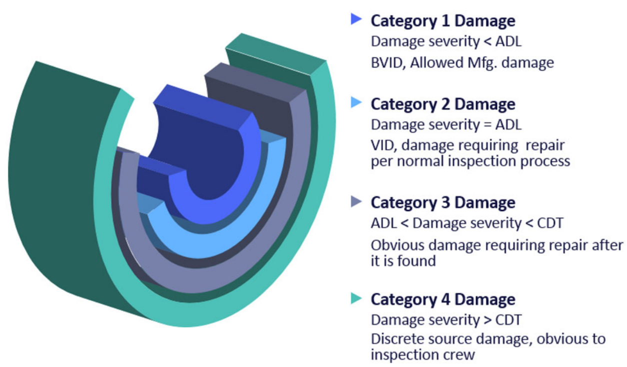

Fig. 5 Different types of damage categories (outer circles have higher priority than the inner circles)

of productivity, customer satisfaction, and competitiveness in the market. Figure 4 shows the influence of design on the wind turbine blades operational life stages, such as manufacturing, operation, inspection, maintenance, etc.

3 Maintenance Plan and Inspection Methods

Wind turbines are subjected to static and dynamic loads caused by fluctuations in wind speed. These loads result in damages and anomalies in the blades, which can lead to the propagation of hidden manufacturing errors, cracks, erosion, delamination, and structural changes. To ensure that the blades are of the highest quality and can perform efficiently over a long period of time, defects must be identified and categorized. Categorizing and prioritizing defects along with devising an inspection and maintenance plan, are essential to ensure that the blades remain in optimal condition and perform efficiently over their operational life. Figure 5 categorizes different types of damages in order to prioritize the required maintenance plan and repair activities. The concentric circles stacked on top of each other represent the prioritization of each category, with the outer circles having higher priority than the inner circles. Defects under the design loading level are categorized as allowable damage level (ADL). In contrast, those more severe than the critical damage threshold (CDT) are classified as serious and require immediate attention. Defects between ADL and CDT can be detected through normal inspection processes and should be repaired immediately. In addition to categorizing defects, it is essential to devise an inspection and maintenance plan to ensure that the blades remain in optimal condition throughout their operational life. This plan must take into account the type and severity of the defects detected. By prioritizing maintenance and repair activities, the overall reliability and efficiency of the wind turbine can be increased, and the cost of maintenance can be reduced.

There are several non-destructive inspection methods available for inspecting wind turbine blades. The selection of the appropriate method depends on factors such as material properties, blade design, manufacturing technology, and economic concerns. The blade is typically inspected for special damage categories in a large area. Regular inspection and maintenance are necessary to ensure the safety and reliability of wind turbines. When it comes to inspecting wind turbine blades, selecting the appropriate non-destructive inspection method is crucial. The damage evaluation capability of the chosen method must be consistent with the severity of the damage present in the material. There are two main categories of non-destructive inspection methods: contact and non-contact methods. Contact methods require physical contact between the sensor and the blade, while non-contact methods do not. Each method has its own unique application depending on the category of damage. Conventional NDT techniques, which fall under the category of contact methods, usually require the sensor to be in close proximity to the blade. While contact methods provide more reliable data and inspection outcomes, access to the blade can be difficult and require specialized equipment, such as an industrial climber or crane, which can be dangerous and time-consuming. In some cases, the blade may need to be removed to implement conventional methods. Safety and efficiency are critical factors when it comes to contact inspection methods. To address these concerns, robotic equipment or human inspectors trained in safety protocols may be used. Non-contact inspection methods, on the other hand, are more flexible and allow wind turbine blades to be inspected on-site without lengthy preparation.

4 Non-contact Inspection and Damage Identification Methods

Some of the most important Non-contact inspection methods include thermography, radiography, machine vision, laser shearography, and microwave testing. Non-contact methods are particularly useful for inspecting hard-to-reach areas or assessing the blade's overall condition. Although non-contact methods are flexible and efficient, the results must be as reliable and conclusive as those obtained by contact methods. This is critical to ensure the safety and reliability of wind turbines. In addition, using non-contact methods reduces wind turbine downtime, and maintenance can be performed with less personnel. Selecting the appropriate non-destructive inspection method is essential for wind turbines' safe and reliable operation. Each method has its own unique advantages and limitations, and the choice should be based on the specific damage category, access to the blade, and efficiency and safety concerns.

4.1 Thermography

Using thermography as a non-destructive testing (NDT) method, it is possible to scan large wind turbine blade (WTB) surfaces for changes in their thermodynamic properties. Thermography relies on measuring temperature differences on the surface of the material, which can indicate areas of damage or defects that are hotter or colder than surrounding areas [26][27]. This method is particularly useful for detecting subsurface damage that may not be visible to the naked eye. Infrared sensors and cameras are commonly used to measure the surface temperature of turbine blades, and the results can be analyzed using specialized software. One advantage of thermography as an NDT method is its non-invasive nature, which means it does not require direct physical contact with the blade. This makes it a safer and more efficient inspection method, as access to the blade can be difficult and time-consuming. Additionally, thermography can be used to inspect WTBs on-site without lengthy preparation, reducing wind turbine downtime and the need for personnel. However, the slow speed of temperature development can limit early fault diagnosis using thermography. It is also important to note that infrared photography techniques have not been widely utilized in the industry to detect damages to WTBs and assess their health. Nevertheless, several recent studies have explored the use of thermography in WTB inspection [28]. Infrared sensors and cameras are commonly used to measure the surface temperature of turbine blades [29][30]. Despite its effectiveness in detecting damage to wind turbine blades, thermography has limitations regarding early fault diagnosis. This is mainly due to the slow speed of temperature development, which means that changes in temperature due to damage may not be immediately apparent. As a result, thermography may be more suitable for detecting and assessing damages during routine inspections rather than for identifying early-stage faults that require immediate attention [28]. Figure 6 depicts a temperature scheme and thermogram results obtained using an infrared camera. Based on the observed temperature difference, some damage appears to the subsurface of the WTB near the hub. Despite its potential, infrared photography techniques have not been widely utilized in the industry to detect damages to WTBs and assess their health, as noted by Yang et al. [30]. Moreover, Galleguillos et al. [31] utilized automated aircraft equipped with infrared thermography (IRT) to inspect wind turbine blades using unmanned aerial systems (UASs). To determine the best inspection parameters, passive IRT was employed to assess the feasibility of detecting defects. Inspections were conducted at various lengths and distances. According to the study, combining IRTs and UASs may decrease inspection times for short-term evaluations. Munoz et al. [27] have developed an innovative method for detecting blade icing without physical contact

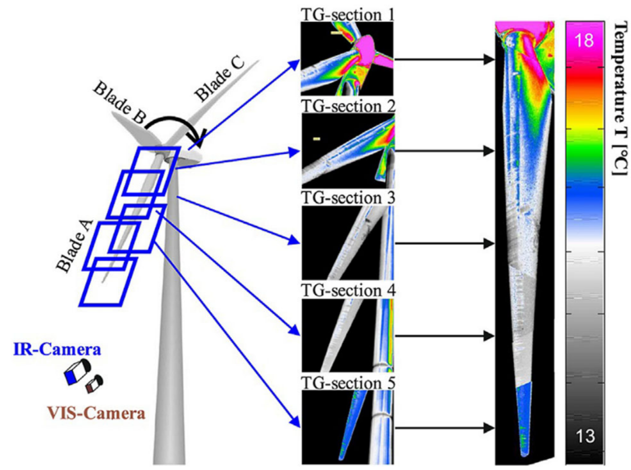

Fig. 6 Scheme of the thermography technique and the thermogram results [36]

using thermal infrared radiometry. Thermographic analysis of offshore wind farms was conducted by Doroshtnasir et al. [32]. It is possible to perform operations remotely using a data processing algorithm, which differs from the common thermographic photograph analysis method. Huang et al. [33] proposed a continuous-wave laser thermography system and a continuous-line laser thermography method [34] for monitoring WTBs. It operates under rotational conditions by generating thermal waves and recording the corresponding wave propagation with an infrared camera. Sanati et al. [35] examined two types of thermography, including passive and active pulse thermography as well as step heating and cooling thermography. It is also capable of monitoring WTB defects, where image processing plays a key role in accurately detecting internal defects. However, it is difficult to highlight the effect of blade damage on temperature and eliminate the effects of other factors. One advantage of thermography is that it can be performed without requiring any direct contact, making it a non-invasive method for evaluating different applications. Passive and active pulse thermography, as well as step heating and cooling methods, have been evaluated for their effectiveness in detecting faults and damage. Passive thermography requires thermal properties that are higher or lower than ambient temperatures, which makes it suitable for monitoring blades in a scene or diagnosing critical conditions. In contrast, active thermography requires energy to create thermal contrast, making it necessary for most parts being inspected, as they are typically in equilibrium with their surroundings. Despite the benefits of thermography, its use in industry for detecting damages to wind turbine blades and assessing their health is still limited. Therefore, further research is needed to optimize inspection parameters and improve the accuracy and speed of early fault diagnosis. The Fraunhofer Institute for Wood Research Wilhelm Kloutz Institute (WKI) has developed an advanced non-destructive testing method called heat flow or active thermography. This method involves recording the surface temperature distribution after thermal stimulation to detect any abnormalities or defects. In addition to active thermography, BAM, the Bundesanstalt für Materialforschung und Prüfung, has also adopted passive thermography to maintain and inspect wind turbines in a safer and more cost-effective way. Passive thermography involves utilizing natural temperature curves, wind, or solar radiation as sources of thermal excitation, without the need for external sources. The project uses an infrared camera developed by InfraTec equipped with a cooled detector and high thermal resolution to measure the surface temperature of the rotor blades.

Various heating sources such as flashes and halogen lamps are commonly used in active thermography to heat objects, but wind turbines cannot use this method due to their large size and shape. However, passive thermography can be utilized as a non-destructive testing method for wind turbine blades. In passive thermography, the blade is heated by solar radiation, typically around sunrise or sunset, or cooled by solar radiation, generally around sunset. This allows for measuring temperature differences on the blade's surface, which can indicate potential defects or damage [37]. This method has been utilized to detect subsurface defects in various materials, including metals [38], composites [39][40], and concrete [41]. Meinlischmidt and Aderhol [37] employed passive thermography to identify internal structural features and subsurface defects such as poor bonding and delamination. Beattie and Rumsey [42] used thermography to inspect wood-epoxy composite blades at 13.1 m and fiberglass blades at 4.25 m. During this experiment, the root portion of the blade was determined to be defective. Shi-bin [43] applied infrared heat waves to examine the blade for subsurface defects such as foreign material and air inclusions. Nieß et al. [44] employed active thermography to inspect the internal damages of WTB parts by using two different heat sources. IR lamps were used as heat generators in the laboratory setup, while the sun was the heat source in the other setup. Although there were differences in recognizing surface defects, both methods could identify internal anomalies. However, the laboratory setup was unable to capture surface features. Galleguillos [31] conducted a new series of tests on the blades of the wind turbine that had been installed. This study examined the thermal images of blades obtained by a camera mounted an unmanned aerial vehicle (UAV) by mounting an infrared camera on a drone, demonstrating the speed with which data can be collected and analyzed. Various climatic conditions have also been examined using thermal imaging to identify internal blade characteristics [45][46]. According to Doroshtnasir [32], a new technique for passive thermography is being developed to allow for the remote inspection of wind turbine blades. The experiment utilized a novel image processing technique to eliminate environmental reflections as a disruptive factor and improve thermal contrast. In various studies, researchers have investigated the use of thermography to detect defects in a wide range of materials, including composites and metals. Lizaranzu et al. [47] evaluated the capability of active thermography in identifying defects in composite structures manufactured by three different methods, including vacuum bag compaction, adhesive joining, and resin infusion molding. These composite structures contained controlled defects similar to anomalies in turbine blades created during manufacturing and operation. The authors recommended that the inspection strategy for composite structures should be determined based on their size, shape, material, and configuration. Several different types of holes, including flat-bottomed holes embedded in high-density rubber, medium-density rubber, and fiberglass-reinforced polymers, were investigated in a study by Lahiri [48]. An investigation of subsurface fatigue damage in adhesive joints between fiber reinforcement polymer components was conducted by Shin [56] using pulse phase thermography (PPT) [49]. Maierhofer used pulsed and lock-in thermography to investigate the phase differences in steel and carbon fiber-reinforced plastics (CFRP) [50]. A comparison was also made between the spatial resolution calculated from flash thermography and locked thermography data collected at different frequencies. In another study, Almond used long pulsed thermography to detect FBH at different sizes and depths introduced in different materials, including aluminum alloy, mild steel, and stainless steel, and a CFRP composite plate. In order to improve the contrast of subsurface defects in captured images, different image processing methods have been established [51]. Maldague and Marinetti [52] offered PPT taking advantage of both pulsed and locked thermography. By periodically heating the surface with a modulated halogen lamp, locked thermography can be used to detect deeper defects. It is possible that pulsed thermography will not be able to detect a fault as quickly as pulsed thermography [53] [54]. The PPT (Pulse Phase Thermography) technique utilizes a transformation-based algorithm, such as the Fast Fourier Transform (FFT), to convert time domain data into frequency domain data. Pawar conducted a study on low-velocity impacts resulting from barely visible impacts and examined an example of such damage using this technique. The damage was initially calibrated using a blind frequency [55]. This is the limited frequency at which subsurface defects can be discerned from recorded thermal data at a certain depth. The depth and blind frequency relationships of a specimen with barely visible impact damage are then determined. Using the PPT method proposed by Castanedo, defects are inspected successively at different depths via an interactive method involving parameters such as time, frequency resolution, and data storage

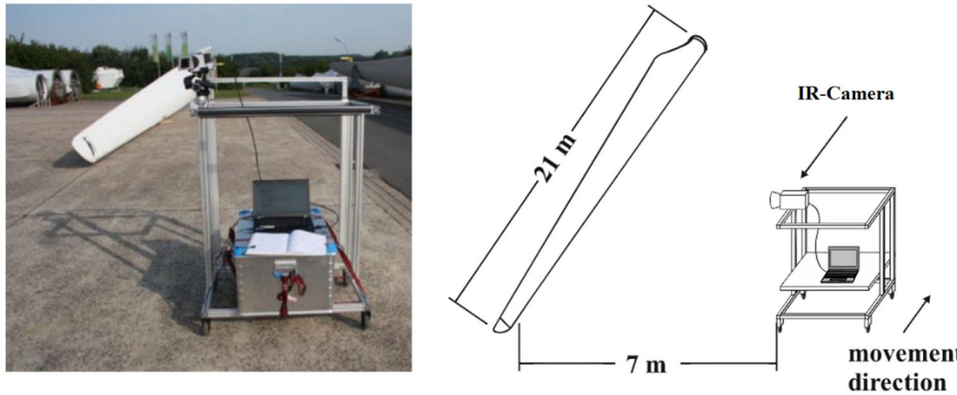

Fig. 7 Passive thermography experiment [32]

capacity [56]. An interactive method was proposed to determine the depth of artificial defects in CFRP samples with artificial defects at different depths. Phase contrast and blind frequency were combined to determine the depth of artificial defects in CFRP samples with artificial defects at different depths. By reconstructing thermographic signals that are derived from simple equations of heat conduction, we can enhance our ability to detect thermal signatures associated with internal defects [57]. By utilizing thermal signatures of high quality, the signal-to-noise ratio (SNR) can be improved, while the blurring of images can be reduced, and sensitivity can be enhanced [58]. Step-heating thermography has recently been demonstrated to produce reliable results using this method [59]. In addition to providing greater contrast between areas of healthy skin and areas of subsurface defects, matching filters (MF) can also serve as a tool to enhance the contrast between such areas. [60][61]. The Passive thermography experiment and position of the blade relative to the IR camera shown in Fig. 7. The thermography's ability to detect defects when the blade is heated by the sun is evaluated in order to determine the most favorable conditions for revealing defects.

The temperature distribution profiles shown in Fig. 8b are plotted with the rows depicted in Fig. 8a. Based on the significant contrasts observed between the defects, it is evident that the deeper the defect, the less noticeable it is from the surface to the bottom. Raw thermograms fail to detect minor defects located deep within the plate, making detecting defects larger than 4 mm difficult. Additionally, the defects located in the middle of the plate are more apparent than those located near the edges. The non-uniform heating causes a difference in thermal energy between the middle and boundaries of the sample. The temperature distribution profiles during step heating thermography of all pixels along the lines shown in Fig. 8a are illustrated. Figure 8c was obtained after 75 s of heating. The smallest diameter defects in the last row failed to generate strong enough signals to be easily detected. Step-heating thermography is more effective in detecting internal defects than pulse thermography, as the object's surface is uniformly heated, as shown in Fig. 8c.

4.2 Radiographic Testing

Turbine manufacturers are deeply concerned about the subsurface requirements of turbine blades, as any internal defects can significantly impact the performance and quality of the blades. It is therefore crucial to ensure that the blades are thoroughly examined from multiple perspectives to ensure their durability and reliability. One of the most effective methods for detecting internal defects in turbine blades is using radiography. By examining the subsurface of the blades, radiography provides a preventive maintenance solution that can help identify any potential issues before they become major problems. There are several possible uses for X-rays, including X-ray tomography, which has made it increasingly possible to study the internal properties of a material in recent years. X-ray tomography allows for the visualization of materials in three dimensions, providing a more comprehensive understanding of the internal structure of an object. However, X-ray radiography is often restricted in the field due to safety concerns and high energy consumption. This means that turbine blades cannot always be accessed from both sides, making it difficult to obtain a complete picture of the subsurface defects. To overcome these limitations, gamma ray radiography is often used instead. Gamma rays have a shorter wavelength than X-rays, making them ideal for imaging thicker objects. Additionally, computed tomography (CT) has become increasingly popular in recent years due to increased spatial resolution, availability of X-rays, and reduced acquisition time. [62]. Utilized an optical microscope, while X-ray computed tomography was employed to investigate the fracture phenomena of composite sandwich panels in WTB. Fracturetographic analysis revealed partially resin-filled grooves influenced crack propagation patterns and fracture mechanisms. Biaxial compression was found to cause delamination and foam cracking. As determined by X-ray computed tomography, microcracks were observed both in the resin and at the interface. Furthermore, radiography was performed not only on the bearings but also on the panels themselves. Reid et al. [63] introduced a method for detecting plastic deformation by utilizing the Neutron Bragg

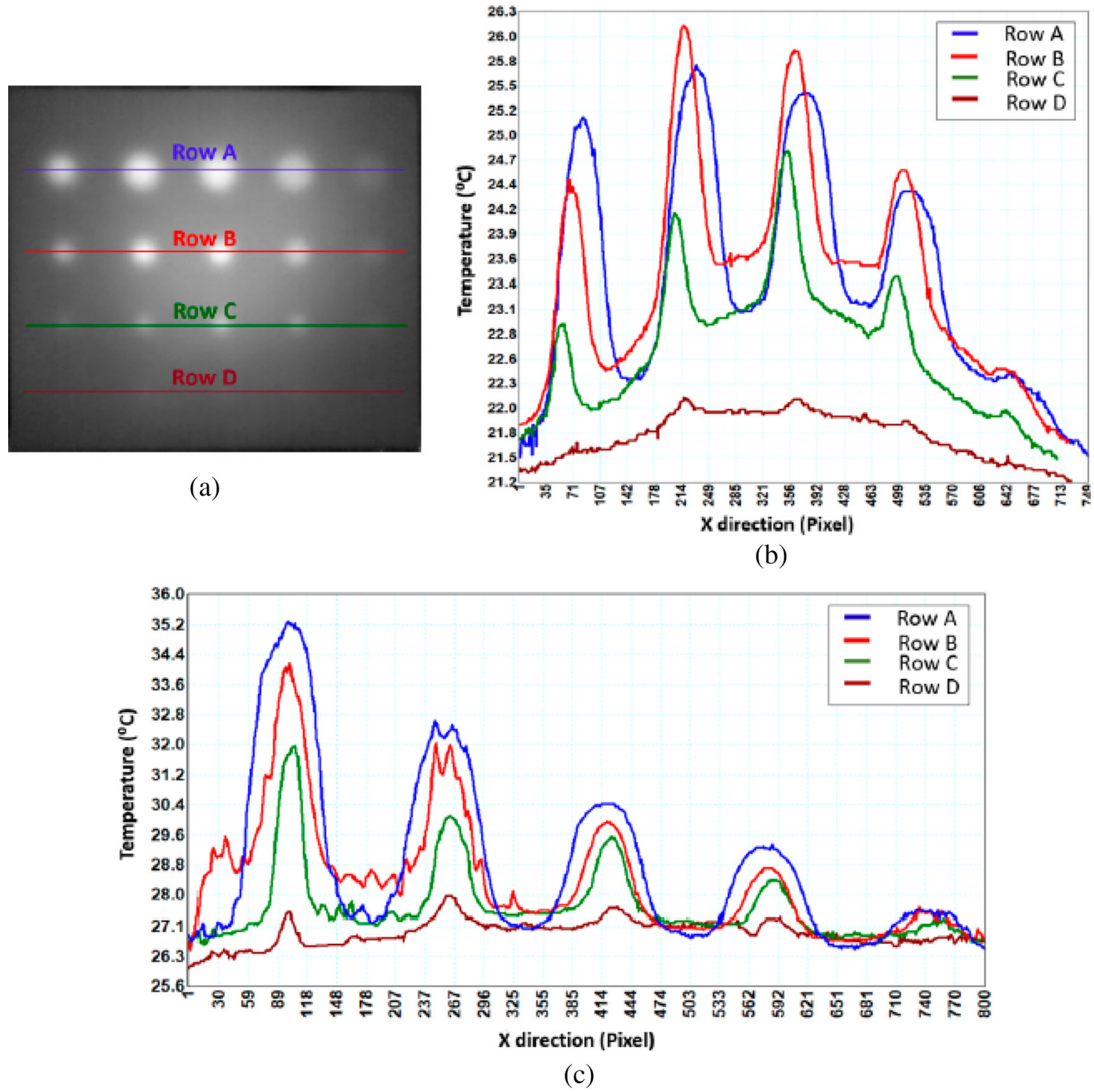

Fig. 8 Temperature profile positions. **a** Analyzing the temperature profiles of different locations, **b** pulsed and **c** an analysis of temperature measurements during step heating. [35]

edge to generate 2D maps. The findings demonstrate a significant correlation between load and Bragg edge width. It is important to note that the compressive strength of WTB materials is directly dependent on the fiber orientation, as it determines the orientation of the fibers. In order to accurately identify fibers, Emerson et al. [64] segmented X-ray tomography images. Fantidis et al. [4] have developed a portable radiographic testing system capable of on-site inspection of WTBs. The MCNPX code was utilized with a range of radiography parameters to design this portable neutron radiographic system, incorporating a SbeBe source. Jasinien et al. [2] applied ultrasonics and radiography techniques to treat prostate cancer. A pulse-echo technique combined with immersion techniques in this area is used for research. This approach enables the identification of fault shapes and sizes. Additionally, a pattern recognition technique is used to detect defects using ultrasonic and radiographic techniques.

4.3 Machine Vision

Machine vision is a technology that utilizes sequences of two-dimensional and three-dimensional images captured from different viewpoints to determine objects' position and location based on stereoscopic vision principles [15]. With significant advancements in computer science and optics, machine vision-based approaches are commonly used for damage detection, dynamic identification, and more [65]. This technology enables image processing algorithms to

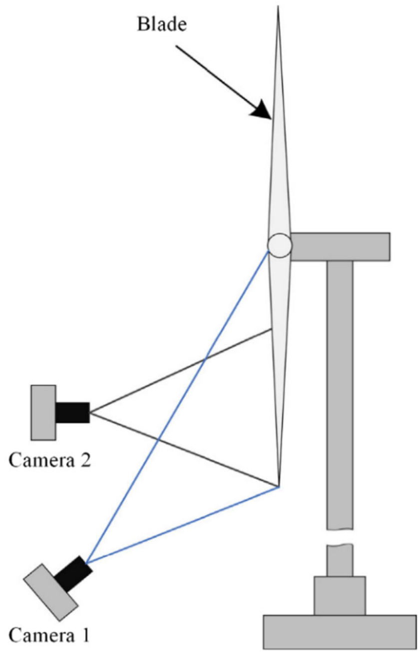

Fig. 9 Prototype of the machine vision-based detection technology by referring to [70]

detect objects more accurately and efficiently. At the same time, the effects of environmental factors on machine vision-based diagnostic methods are less pronounced than those on other diagnostic methods. Machine vision technology is also cost-effective and efficient for detecting low-pressure surface buckling and analyzing turbine blades in service. Additionally, it can detect cracks, scratches, and other external surface damage with high accuracy. A prototype based on machine vision is shown in Fig. 9, which utilizes the parallax principle to obtain images from two different positions for binocular vision detection of blade information. The detection system comprises an image acquisition system, an image processing process, and an identification system [66]. It is particularly necessary to have high-end imaging devices and data processing capabilities to perform line monitoring [67]. With this technology, human resources are also less exposed to hazards associated with wind farm inspections [68]. Johnson et al. [69] developed a stereo-videogrammetric system for monitoring the motion of the airfoils and turbine blades. Using videometry, Yang et al. [70] developed a method for detecting blade deformations and understanding the structural behavior of large-scale WTBs. The displacement of turbine blades can be captured using image processing techniques such as edge detection algorithms, matching algorithms, and others, as Wu et al. [71] demonstrated. In order to measure the accumulation of ice on WTBs in operation, Akhloufi et al. [72] developed an algorithm for image processing and computer vision. The authors of Poozesh et al. [73] performed 3D digital image correlation (3D DIC) to capture the geometry of a WTB"s surface, the deformation of the blade, and the strain on the blade surface over a large area. Moreover, Poozesh et al. [74] measured WTBs with multiple cameras and 3D point tracking techniques. Detection of damage must be automated as part of a WTB maintenance program. In their paper [75], Stokkeland et al. proposed using autonomous vehicles to recognize and track wind turbines and their blades using unmanned aerial vehicles (UAVs). A Kalman filter was used for tracking, and a Hough line transform was used for recognition. A crack detection framework for WTBs was proposed by Wang et al. Using UAV images that use Haar-like features [76]. The vision-based damage detection system developed by Moreno et al. for WTB surface defects is based on deep learning using convolutional neural networks (CNN). Three different types of damage were classified by CNNs trained on real defect images [77]. Increasing the number of training data sets makes it possible to achieve a higher classification accuracy than that achieved by the 81.25% classification accuracy. Denhof et al. [78] developed a deep learning system for the automated detection of optical surface defects in WTB. The researchers studied nine CNN architectures to compare the classification performance to varying training data. The ResNet50 model demonstrated the best median classification accuracy, which satisfied the classification accuracy and runtime requirements. Shihavuddin et al. [79] built a faster R-CNN deep learning system to classify defects in wind turbine blades using a drone for image capture. They created a bank of images containing four different types of surface damage and used 60% of the images for training and the remaining for testing. Through advanced data augmentation techniques, they were able to achieve a precision of 81.10% using the Inception-ResNet-V2 model, which was comparable to the precision achieved by humans. Herraiz et al. [80] employed a lightweight hexapod robotic system for the inspection and maintenance of wind turbine blades. The proposed system offers good accessibility, flexibility, and versatility. It can be installed on a UAV and easily transported to the inspection area. The robot can make omnidirectional movements with three degrees of freedom (DOF) legs. Various inspection equipment, such as a camera for visual inspection and macro-fiber composite (MFC) sensors for acoustic emission (AE) testing, can be installed on the robotic system.

4.4 Laser Shearography Testing

Speckle pattern shearing interferometry is a powerful tool for identifying and measuring various defects. This technique, similar to holographic interferometry, uses coherent laser light for non-destructive inspection, strain measurement, and vibration analysis. It is extensively used in industries such as aerospace, wind turbine blades, automotive, and materials research. Shearography produces interferometric images

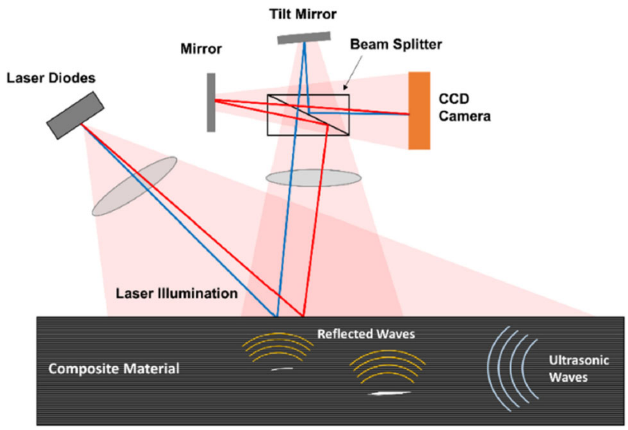

Fig. 10 Composite defect detection using acoustic shearography [83]

that reveal various types of damage, including discontinuities, delaminations, impact damage, porosity, wrinkles, and other defects. Non-destructive shearography uses a common path laser imaging interferometer to determine the first derivative of out-of-plane deformation caused by mechanical loads and thermal expansions. Deep anomalies can be detected and measured by stressing the test part through heat, blade pressurization, or mechanical bending load. This includes fiber waves, impact damage, delamination, cracking, or disbonding. The laser light source integrated into the shearography camera illuminates the target area, which can range from several square centimeters to several square meters, depending on the defect's size. By interfering with laser speckle patterns, shearography visualizes changes in surface strain. As an interferometric system, shearography is particularly robust against external vibrations, making it an ideal tool for non-destructive testing in industries. Electronic strain pattern interferometry (ESPI) is another technique related to holography that provides full-field measurements. It is a non-contact technique that directly measures surface displacement. On the other hand, speckle interferometry measures the spatial derivative of displacement rather than the surface displacement itself. When a load or displacement is applied to a speckle pattern, a speckle interferometer measures the difference between the speckle pattern recorded before and after the load is applied. The correlation between the speckle patterns produces a contour map of the fringe pattern, as shown in Fig. 10, which can be further processed to determine the phase of the correlation fringe pattern and obtain quantitative information. This technique enhances the contrast of the fringe pattern, making it easier to detect and measure various types of defects. Shearography and ESPI have several advantages when used in industrial testing. Shearography is particularly suitable for non-destructive research due to its high tolerance to environmental disturbances as an interferometry technique.

Li et al. [81] introduced a robot-assisted shearography system for inspecting wind turbine blades. Experiments were conducted to evaluate the applicability of shearography for on-site inspections. However, limitations were encountered in the detection of defects in high-stiffness areas produced by fiber glass. Therefore, the researchers suggested that the shearography system could detect subsurface damages within WTB. Schäfer et al. [82] presented a collision-free automated flight approach for inspecting wind turbines while considering the limitations of the GPS navigation system. They utilized a multicopter unmanned aerial vehicle (UAV) equipped with GPS and LiDAR laser sensors to overcome the limitations of GPS navigation, such as signal obstruction. The implemented navigation system was based on 3D mapping, path planning, and distance control. To conduct indoor tests instead of GPS information, an IR tracking system was used to estimate the position.

4.5 Microwave Testing

Microwaves are a type of electromagnetic wave that can be used to detect defects in composite materials by measuring changes in the electromagnetic and electromechanical properties of the materials. This technology offers several advantages, such as non-contact inspection, no need for surface-attached transducers or coupling agents, an operator-friendly interface, good reproducibility, and non-ionizing radiation. In the case of glass-fiber polymer composites, microwave testing can be carried out using two main inspection approaches: near-field and far-field. The near-field approach involves using the evanescent field of an open-ended coaxial line or an antenna's non-radiative/reactive region that exists in the immediate vicinity where mature propagating waves have not yet been formed. On the other hand, the far-field is the region of operation for most antennas, where the radiation pattern does not change with distance, and absorption of the radiation in the far-field region does not feed back to the transmitting antenna. To perform a far-field inspection, as shown in Fig. 11, a monostatic configuration, Fig. 11(a), or a bistatic configuration, Fig. 11(b), can be used. In the monostatic system, as shown in Fig. 11(a), the transmitter and receiver share an antenna with a circulator. The circulator is a three-port passive non-reciprocal microwave device that routes microwave signals from the transmitter to the antenna and from the antenna to the receiver, preventing direct transmission of signals from the transmitter to the receiver. Although the monostatic system has more compact dimensions than its bistatic counterpart, less isolation can lead to significant leakage. Microwave testing effectively detects defects such as voids, delaminations, and internal cracks in composite materials. By using near-field and far-field approaches, microwaves can be directed to a specific material area, allowing for accurate detection and

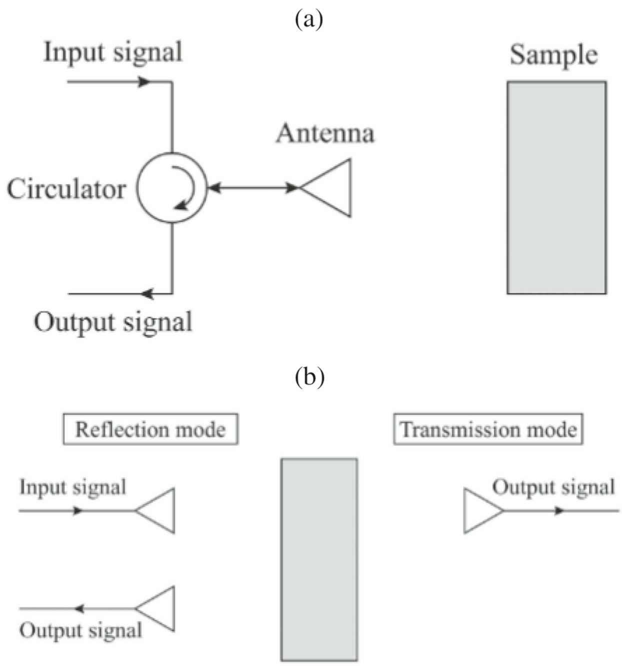

Fig. 11 Two typical antenna configurations for far-field microwave inspection. **a** Monostatic configuration. **b** Bistatic configuration [88]

analysis of defects. However, it is essential to note that the accuracy of microwave testing may be affected by several factors, including material composition, moisture content, temperature, and frequency. Therefore, proper calibration and control of testing conditions are critical to ensure reliable results. Despite these limitations, microwave testing is a valuable non-destructive testing technique for composite materials, offering advantages over traditional methods such as ultrasound and X-ray. Blanche et al. [84] used frequency-modulated continuous wave (FMCW) radar analysis to detect surface and internal damage in a decommissioned WTB. The return signal amplitude (RSA) was analyzed to detect composite properties such as delamination and water ingress in the composite structures. Experimental tests were conducted to evaluate the sensitivity of K-band FMCW in detecting delamination in composite structures. The authors claim that FMCW is applicable for identifying porosity in WTB structures.

Permittivity measurement is an important technique for characterizing the electrical properties of materials. Resonant and non-resonant methods are the two main types of permittivity measurement methods. Resonant methods are typically used to measure permittivity values at specific resonance frequencies, providing high accuracy and sensitivity. Non-resonant methods, on the other hand, can characterize materials over a frequency range, allowing for a more comprehensive analysis of the material's electrical properties. Regarding sample preparation, permittivity measurement methods can be categorized as either intrusive or non-destructive/non-invasive. Intrusive methods, such as the resonant and transmission lines, require cutting and machining test samples. These methods provide accurate measurements but can be labor-intensive and may not be permissible for some materials or components. Non-destructive/non-invasive methods, such as the open-ended probe method and free space measurement, do not require cutting or machining of test samples. Instead, these methods use probes or antennas to measure the material's electrical properties without physically altering the sample. These methods are generally less invasive and less time-consuming than intrusive ones, making them more suitable for certain applications. For example, the open-ended probe method involves placing a probe near the surface of the material being tested and measuring the electrical properties of the material at the probe's resonance frequency. This method is non-destructive and can provide accurate measurements of the material's permittivity.

On the other hand, free space measurement involves measuring the reflection and transmission of electromagnetic waves as they pass through the material being tested. This method is non-destructive and can accurately measure the material's permittivity over a wide range of frequencies. In conclusion, the choice of a permittivity measurement method depends on the specific application, the type of material being tested, and the level of accuracy required. Both resonant and non-resonant methods have advantages and disadvantages, and the decision to use an intrusive or non-destructive/non-invasive method depends on the availability of test samples and the analysis goals [88].

5 Integration of Industry 4.0 Technologies with Non-Contact NDT Methods

Industry 4.0, also known as the fourth industrial revolution, is the latest development in the industrial sector, focusing on digitizing and integrating physical and virtual systems [85]. Non-contact NDT methods do not require direct contact with the material being inspected, which reduces the risk of damage to the surface of the wind turbine blade during the inspection. Integrating non-contact NDT methods with Industry 4.0 technologies such as the internet of things (IoT), robotics, and artificial intelligence can offer several benefits [86]. This can help extend the blade's lifespan and reduce the need for costly repairs. Integration of non-contact NDT methods with Industry 4.0 technologies improves the speed and accuracy of inspections [87]. This can help reduce inspection times and improve the overall efficiency of wind power generation. NDT methods that can provide digital data are able to be integrated with Industry 4.0 technologies for real-time analysis and remote monitoring [88]. This can help reduce the need for manual data collection and analysis, saving time and reducing the risk of errors.

In addition, Industry 4.0 technologies can be used to monitor the condition of wind turbine blades continuously and predict potential faults before they occur. This can help prevent unexpected downtime and reduce maintenance costs. However, there are also challenges to integrating NDT methods with Industry 4.0 technologies, such as the need for specialized expertise, the cost of implementing new technologies, and the need for reliable inspection methods [89]. Therefore, not all NDT methods may be optimal for integration with Industry 4.0 technologies, and it may be necessary to adopt available methods to take full advantage of the benefits of Industry 4.0. NDT methods that are suitable for integration with Industry 4.0 technologies typically have the following characteristics:

- Digital data output: The NDT method should produce digital data that can be easily collected, stored and analyzed using Industry 4.0 technologies. This allows for real-time data analysis and predictive maintenance.
- Automation capability: The NDT method should be capable of being automated to enable integration with Industry 4.0 technologies. This can improve the speed and accuracy of inspections while reducing the need for manual labor.
- Remote monitoring capability: The NDT method should have the capability to be remotely monitored and controlled. This allows for real-time data analysis, as well as remote control and adjustment of the inspection process.
- Accuracy and sensitivity: The NDT method should be highly accurate and sensitive to detect small defects and discontinuities. This is essential for early detection of defects, which can help prevent costly downtime.

Integrating non-destructive testing (NDT) methods with Industry 4.0 technologies for wind turbine blades has great potential to improve the reliability and safety of wind turbines and reduce maintenance costs.

6 NDE 4.0

Predictive maintenance strategies aim to identify issues before they cause downtime, reduce maintenance costs, and improve overall equipment effectiveness. NDE 4.0 incorporates Industry 4.0 technologies to enhance NDE processes' speed, accuracy, and efficiency. Implementation of NDE 4.0 for turbine blades is likely to involve the integration of advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Finite Element Method (FEM), Augmented Reality (AR), and digital twins (DT). This will enable real-time tracking and monitoring of components, predictive modeling, and optimization of component functionalities. One approach to automatically and efficiently collect information about the components in wind turbines is through sensors and IoT technologies. The sensors can be placed on the components and monitor their condition, performance and usage in real-time. The collected data can then be transmitted to a central database via IoT technologies. This approach can provide a constant stream of data, reducing the need for manual data collection and ensuring the data is up-to-date. Another approach is the use of AR and computer vision technologies. Using these technologies makes it possible to automatically recognize and identify components and track their status and performance. This can be done through the use of cameras, image recognition algorithms and machine learning models. This approach can provide a more comprehensive view of the components, reducing the need for manual data collection and ensuring that all data is accurately captured. All these elements of digital technologies can be integrated into digtital twins. Digital twins are virtual representations of physical assets, such as wind turbine components, that mirror their real-world counterparts in real-time. By using digital twin technology, it is possible to track and monitor the components, collect data about their performance and usage, and predict their future behavior. This approach can provide a comprehensive view of the components, making it easier to implement predictive maintenance strategies. A framework considering the interactions and elements of the physical twin and its digital twin is illustrated in Fig. 12.

Integrating AI, FEM, and AR can significantly enhance the implementation of digital twins for predictive maintenance in the wind energy sector. This combination can create a powerful predictive maintenance system that leverages real-time data analysis and simulation to identify critical turbines and inform maintenance activities. AI can be used to analyze the data from the digital replica and provide predictive maintenance recommendations, helping to identify potential problems before they occur. FEM can be used to perform simulations and stress analyses, providing insights into the structural integrity of components and helping to identify potential failure points. AR can be used to display the digital components in a 3D model, making it easier for maintenance teams to visualize the components and understand how they fit together. In this configuration, digital twin contributes to identifying critical turbines, components, and positions, as depicted in Fig. 13.

The use of digital twins in floating offshore wind turbine blades is becoming increasingly important due to the need for non-contact distant inspection. Traditional inspection methods for offshore wind turbine blades often require physical access, which can be dangerous and costly. Digital twins allow for remote monitoring and analysis of the condition and performance of the blade, which can help prevent costly downtime and improve safety. The complexity of loads in floating offshore wind turbine blades makes digital

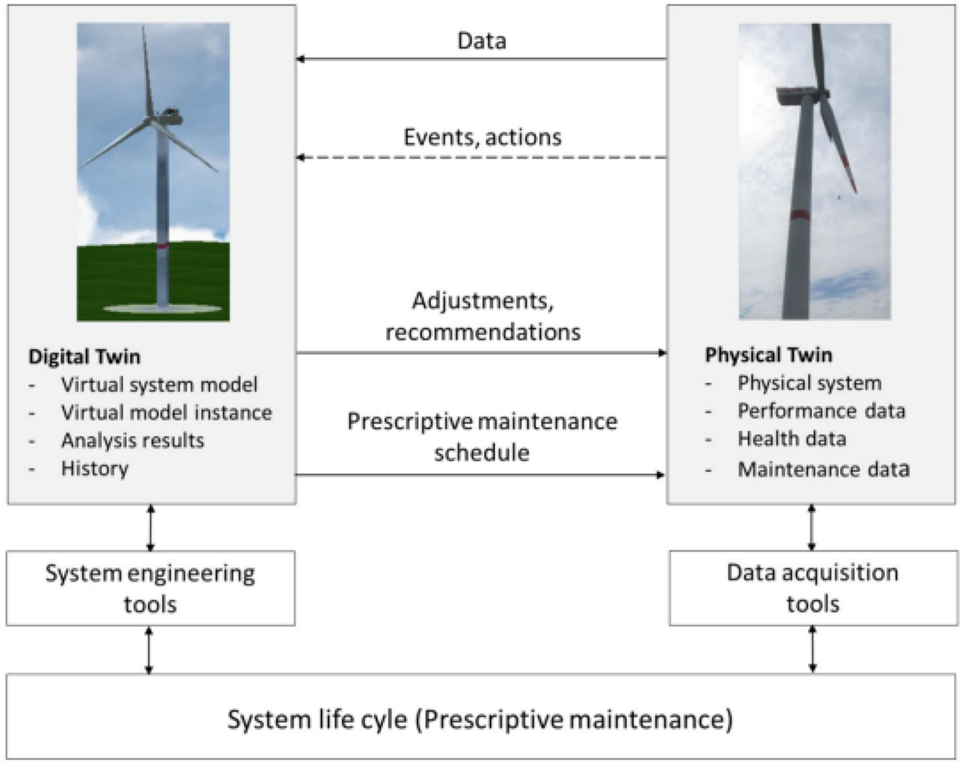

Fig. 12 Interaction between the digital and physical twins [90]

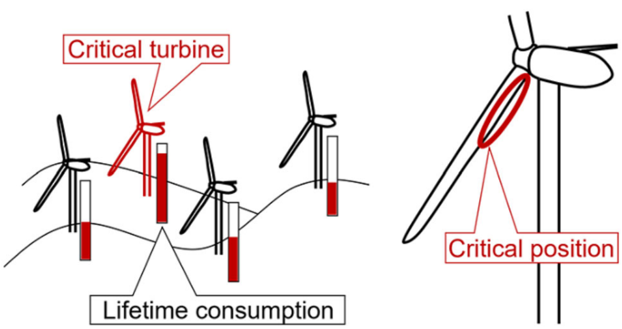

Fig. 13 Using digital twins to identify critical wind turbines and positions [91]

twins particularly significant. Digital twins can provide real-time simulations of the loads acting on the blade, allowing for early identification of potential issues and optimizing the blade design.

Over all, Industry 4.0 adoption of wind turbine sustainability will become increasingly important as it enables efficient asset management, reduces downtime, and improves operational efficiency. However, clean energy production still has excellent potential for more sustainability if solutions to the problems of wind turbine inspection and maintenance are found. One of the problems is the maintenance of energy supply sites in different parts of the world by entities other than the leading manufacturers of wind turbines. As a result, the information related to the inspection, maintenance, replacement and overhaul of different parts is not stored. Therefore, especially in parts of the world with very different environmental conditions, the type of problems encountered and the parts used will be very different.

7 Techno–Economic Aspects of Non-Contact Inspection Methods

Wind farm maintenance providers ensure wind turbines' optimal performance and longevity. As such, selecting the most suitable inspection method is critical to the success of their maintenance services. To achieve this, they must consider various factors, including the wind turbine's location, design, climatic conditions, and manufacturing and operation-induced defects. Moreover, an organization's financial resources play a significant role in determining the availability of building facilities, employee training, and maintenance strategies. Therefore, it is crucial to consider both technical and financial concerns when selecting an inspection method. The interdependence of these two issues is illustrated in Fig. 14, which shows the impact of financial resources on the maintenance and performance of wind turbines. Drones and autonomous vessels are increasingly used for offshore wind farm inspection and repair. Drones monitor the tower and nacelle, including blades, without

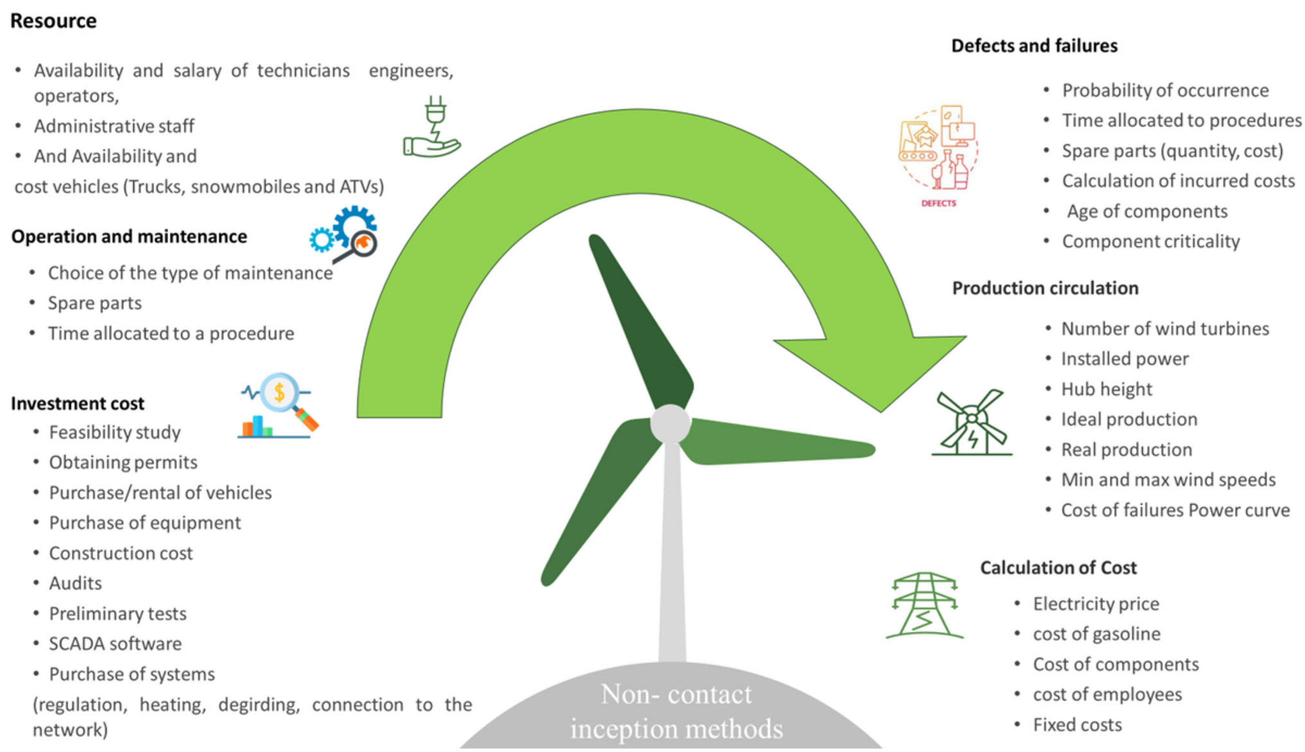

Fig. 14 Non-contact inspection method concerns based on techno–economic analysis

shutting down, while autonomous vessels inspect foundations and underwater parts. Drones can be deployed with different types of sensors for structural health monitoring. These technologies improve efficiency and safety, increasing energy production and reducing downtime. If necessary, both devices can be equipped with additional instrumentation, e.g., non-destructive sensors such as infrared cameras and laser scanners [92]. Combining drones with other non-contact NDT technologies allows wind turbine blades to be inspected more efficiently and quickly, reducing inspection duration. Moreover, drones can perform inspections more efficiently and are less risky than individuals using ropes and harnesses. However, depending on the operating conditions, such as offshore wind farms, there may be a need for drone flight control systems. By integrating drone technology and other non-contact NDT technologies, maintenance providers can identify potential anomalies more accurately while reducing the risks associated with human inspections. This approach provides a reliable, cost-effective, and safe solution for wind turbine inspections managing technical and financial concerns while ensuring wind turbines' optimal performance and longevity.

The data acquired from wind turbine blades using drones is often processed for feature extraction to identify any potential damage that may have occurred during the turbine operation. Once the relevant features have been extracted, they are analyzed to determine the extent and severity of any damage that may be present. This allows for the detection, localization, and quantification of the damage, which are important steps in ensuring the turbine's continued safe and efficient operation [93]. Detection involves identifying damage within the blade, which can be achieved through various techniques such as acoustic emission monitoring, vibration analysis, and visual inspections. Localization consists of determining the damage's location within the blade, which can be achieved through techniques such as thermography or ultrasonic testing. Quantification involves measuring the size and severity of the damage, which can be achieved through techniques such as digital image correlation or finite element analysis. Incorporating hyperspectral imaging (HSI) with drone-based inspection for wind turbine blades is a promising advancement in the renewable energy industry. By utilizing the HSI sensors on drones, this combination can provide comprehensive and high-resolution images of the blade surfaces, leading to the detection and localization of surface, subsurface, and icing damage.

Furthermore, the spectral data obtained by HSI sensors can identify defects invisible to the naked eye, such as those caused by manufacturing defects, material degradation, and environmental factors. Additionally, using drones allows for fast and cost-effective inspection, reducing the need for manual inspection and potential downtime. To further enhance this approach, machine learning algorithms can be utilized to analyze the HSI data and assist in detecting and classifying blade damage. This will help to establish early fault detection, enabling proactive maintenance and reducing the likelihood of unexpected downtime. Further research can explore the optimization of the HSI sensors and drone flight patterns for maximal efficiency and comprehensive coverage of the blades [94].

8 Conclusion

Non-contact NDT methods are highly suitable for integrating with Industry 4.0 technologies for inspecting wind turbine blades. This integration provides maintenance providers various benefits, including improved efficiency, reduced costs, enhanced safety, and predictive maintenance capabilities. The discussion and analysis of these techniques resulted in the following conclusions:

- Drones equipped with machine vision sensors and cameras, laser shearography, and microwave testing can provide a wealth of data that can be analyzed using Industry 4.0 technologies. This data can detect anomalies, monitor performance, and identify potential defects or failures, enabling maintenance providers to take proactive measures to prevent downtime and optimize the wind turbine's performance.
- Thermography has a relatively short inspection time (150 s) and seems sensible for internal defects. It is contactless, easy to implement (especially in reflexive mode), low cost, and has low user requirements. However, its limitations for high thickness measurements must be considered.
- Composite materials can be easily inspected using X-ray CT. However, the effectiveness of this method can vary based on the thickness and size of the defect. Therefore, the evaluation of large-scale CT systems specifically designed for measuring large parts is necessary before X-ray CT systems can be used to measure wind turbine blades.
- Shearography is the fastest method, but it has limited sensitivity to the delamination defects of thick parts. In addition, supplying the required optical equipment may not be cost-effective.
- Microwave testing is a powerful method for inspecting wind turbine blades, and it has a high potential for integration with Industry 4.0 technologies. Its automation and remote monitoring capabilities are particularly strong, while its accuracy and sensitivity are also high.
- Machine vision inspection allows for full-field and fast inspection of wind turbine blades without compromising high resolution and sensitivity. The only limitation is the inability to detect internal defects.

Identifying and diagnosing surface and internal defects of wind turbine blades require the simultaneous use of inspection methods with surface and subsurface detection capabilities. To this end, the integration of inspection methods with Industry 4.0 technologies, such as the Internet of Things (IoT), to implement sensor fusion becomes imperative despite synchronization and integration difficulties. When combining all of these technologies, sensor fusion takes the simultaneous input from multiple sensors, processes the input, and creates an output that is greater than the sum of its parts. By using special algorithms and filtering techniques, sensor fusion eliminates the deficiencies of each individual sensor. Sensor fusion provides a complete set of capabilities that can implement smart inspection and enables various services that can take advantage of these capabilities [95]. In summary, integrating inspection methods with Industry 4.0 technologies entails sensor fusion for complete and comprehensive identification and diagnosis of surface and internal defects of wind turbine blades.

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Declarations

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