Technologies for structural health monitoring of wind turbine blades

An overview of different techniques

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Abstract

Wind turbine structures take a major role in the modern conversion to renewable energy sources and contribute to the creation of a greener world. In recent years, the development and installation of wind turbines have seen rapid growth. However, with the increasing capacity and size of wind farms worldwide, there are growing concerns about the safety and reliability of these installations. Therefore, structural health monitoring and the detection of damage to wind turbines have gained considerable importance in research. Wind turbine blades are particularly susceptible to various types of damage due to environmental influences. This article provides an overview of signal responses, sensors used and non-destructive testing techniques in the field of damage detection on wind turbine blades. The intention of the article is to give an insight into the possibilities of structural health monitoring and at the same time to point out unsolved problems in this field.

Keywords: structural health monitoring, wind turbine blades, damage detection, measurement, non-destructive testing

1 Introduction

Wind power is becoming increasingly important due to the concept of sustainability in energy generation and the expansion of renewable energies. In the first half of 2023, the number of onshore wind turbines in Germany amounted to around 28,500 [1] and the number of offshore wind turbines to 1,500 [2]. Wind turbines are constantly exposed to environmental influences such as changing wind loads or fluctuations in temperature and humidity [3]. For this reason, they are particularly susceptible to failure. According to [4], around 17 % of damage to wind turbines in Germany between 2016 and 2020 is caused by wind turbine blade (WTB) components. This figure shows, that early detection of this damage category is necessary in order to avoid economic losses and ensure the safe operation of the wind turbines. For this reason, structural health monitoring (SHM) of wind turbines is a current focus of research [5]. This review is intended to provide an overview of possible measures for SHM. The focus will be primarily on non-destructive testing (NDT) methods. This is accompanied by a brief explanation of the possibilities for signal evaluation and the different sensor types used for SHM. The idea is to determine which measures are currently important for research and which methods may already be established. The advantages and disadvantages of the methods must also be considered.

2 Material and methods

To explain the relevance of the topic based on reliable data, contact was made with an insurance company that keeps a damage report on wind turbines. Through e-mail correspondence, the questions relevant to the topic were answered on the basis of the damage report.

A literature review was conducted to identify SHM methods used worldwide. The individual methods were classified, described and the respective advantages or disadvantages were presented. Most of the compiled data was taken from previously published papers and reviews available on Google Scholar.

3 Signal based methods for failure detection

Signal-based damage detection methods comprise two main processes:

1. feature extraction and selection
2. pattern recognition

In the first process, the features are identified and selected to quantify the damaged state of the structure.

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The data is condensed into a small data set that can be better analyzed statistically. This is done, for example, by data normalization to eliminate environmental conditions. [6]

Pattern recognition works with algorithms that can determine the state of damage from the extracted features. These can be divided into three signal processing techniques [6]:

- time-domain methods
- frequency-domain methods
- time-frequency-domain

Measured data from sensors in the **time-domain** contains structural information. It can work with linear and nonlinear functions and does not need any frequency transformation for damage detection [5]. Various approaches and models exist for the evaluation of time domain methods. [6] mentions the use of autoregressive models (AR model), autoregressive models with exogenous inputs (ARX models) and autoregressive moving average vector models (ARMAV models).

The methods of time-domain evaluation can be categorized into two subgroups which are statistical-methods and time-domain modal-based approaches. Statistical methods extract structural changes by statistical parameters such as mean value or standard deviation. Results from practical experience show, that the proposed method performed efficiently when "the data of all measured positions transformed into the normal vibration forms and conditions of the intact blade" [5]. Furthermore, it has been determined that the number of points measured is important for damage detection. Studies on time-domain modal-based approaches show that stable operating conditions must be available for this procedure, as environmental influences directly affect the measured signals. The "bagged tree algorithm", which is used for evaluation, achieved an accuracy of 98 %. [5]

Frequency-domain responses are resulting from the conversion of time-series responses into frequency responses [5]. Fourier analyses, cepstrum analyses, spectral analyses or frequency response techniques are used for signal transformation to extract features in a specific time window [6].

The fast Fourier transform (FFT) is often used for signal analysis. It is not suitable for analyzing non-stationary signals because signals like WTB-vibration are weak. In combination with other methods, such as statistical methods (time-frequency-domain [5]), a better accuracy of the signatures of anomalies and outliers can be achieved. The FFT is used to detect running surface faults in bearings and to detect cracks in gears. [7]

Time and frequency-based approaches are used to analyze non-stationary signals. Current signal processing methods in research include the short-time Fourier transform (STFT), the Wavelet transform or Wigner-Ville distribution (WVD). [5]

4 Sensors for failure detection

This chapter is intended to provide a basic overview of the different sensors that can be used for the SHM of WTBs. According to [5], the following sensors are used for non-destructive testing:

- Strain gauges
- Fiber optic sensors
- Accelerometers
- Acoustic emission (AE) sensors
- Piezoeletric (PZT) sensors
- Scanning laser doppler vibrometer (SLDV) sensors

Strain gauges measure the change in strain of the material. Conventional strain gauges consist of a non-conductive carrier and are attached to the surface to measure the change in resistance. The accuracy depends on the installation and environmental influences such as temperature. [5]

Fiber optic sensors measure strain, temperature and humidity. Interferometers and wavelength-based sensors are used to detect damage to WTBs. They transmit the signals with low losses and do not suffer from electromagnetic interference. Fiber optic sensors are more expensive than conventional strain gauges. [5]

The principle of **accelerometers** is based on measuring the acceleration of a mass after the impact of a force that is suspended from a spring. A classification is made between piezoelectric, piezoresistive and capacitive sensors. For an exact measurement, many sensors are required whose position must be known and which each require an external power supply. However, the sensors are inexpensive and resistant to high temperatures. [5]

Acoustic emission (AE) sensors detect cracks, delamination[1], corrosion and detachment. They are made up of piezoelectric crystals that convert mechanical stress energy from the damaged areas into electrical signals. Because the signals from the sources of damage are detected, the sensors must be positioned close to the damage. However, the sensors do not require external excitation and can operate in a wide frequency range. [5]

[1] Delamination refers to the detachment of layers in advertising materials

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The difference between **piezoelectric (PZT) sensors**, accelerometers and AE sensors is that PZT-sensors can act as both sensors and triggers. When it is used as a trigger, the sensors work like the reverse piezoelectric effect, converting voltage into mechanical effects. PZT sensors are very sensitive to structural changes and at the same time inexpensive. However, they should be placed close to the damage. [5]

The velocity sensor **scanning laser doppler vibrometer (SLDV)** is used to measure vibrations. This instrument emits laser beams that are specifically directed at the surface of a structure to analyze the beams reflected from it. The basis of this analysis is the doppler effect, which represents a change between the frequency emitted by the laser source and the frequency reflected by the moving surface. SLDVs can be used for inaccessible areas and work without contact. However, they are expensive. [5]

5 Non-destructive monitoring of WTBs

Non-destructive methods are primarily suitable for SHM of WTBs. Methods that destroy the material, for example through testing, are not considered here. Table 1 summarizes the advantages and disadvantages of the different methods based on the literature reviewed.

5.1 Acoustic emission measurement

Acoustic emission (AE) refers to the emission of elastic (sound) waves with low amplitude and high frequency range within a material. These waves arise from deformation as a result of the release of energy. The process is used during system loading. Elastic waves can also be induced and introduced into the structure and serve as an active SHM method. The waves are converted into electrical signals using piezoceramic sensors. The sensors are mounted close to the surface. Signals with low amplitude must be amplified. However, this also amplifies noise. To eliminate noise, the frequency bandwidth is limited or bandpass filters are used. Data acquisition is then carried out with A/D converters[2] that can operate in a high frequency bandwidth. Analysis parameters that are relevant for the evaluation of AE signals are event counts, rise time, peak amplitude, arrival time, duration, signal energy content and root mean square. [7]

[10] found that the threshold value for processing the sound waves is 45 dB. It was determined that a total of 72 sensors are required to localize damage for a WTB 45 m length. Reducing the threshold value to 40 dB through noise suppression and more complex signal processing could reduce the number of sensors to 32. The accuracy of this method is less than 1 cm [11].

[2] A/D converters are used to amplify signals

5.2 Acoustic measurement

The acoustic-based method analyzes the airborne sound waves to monitor the blade conditions. The acoustic signals are generated and propagated by the structural defects. This is a natural phenomenon. The method analyzes the change in the airborne sound waves during transmission. Cracks, detachments, edge breakouts and holes are examined. The method can be divided into

- passive detection and
- active detection.

In **passive detection**, microphone sensors are installed inside the WTB to record the airborne sound in the cavity. This is illustrated in figure 1. Structural defects change the sound pressure level. Signal processing tools are required to minimize noise. [5]

For **active detection**, loudspeakers are installed inside the WTBs. Microphones are located on the tower of the wind turbines to record the acoustic signals. The damage transmits the sound energy easily through the wall and is detected by the microphones. [5]

The acoustic method is a new, modern procedure. Research in this area focuses primarily on the use of machine learning and the development of wireless systems. [5]

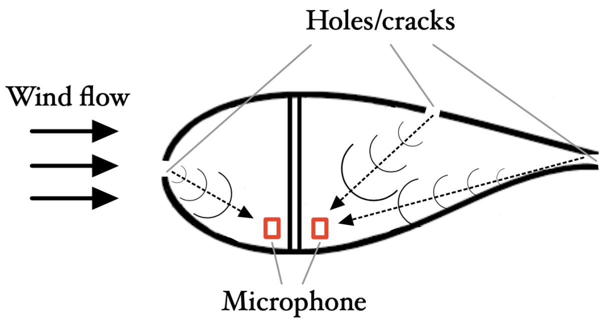

Fig. 1: Schematic illustration of acoustic measurement with passive damage detection (own illustration based on [13])

The method has already been successfully used in a study by [11] to detect cracks and edge breakouts on a 46 m long WTB. In addition to the severity, the location of the damage could also be determined.

5.3 Ultrasonic measurement

The ultrasonic method can be divided into three different types: The pulse-echo, the pitch-catch and the through-transmission [14, 15]. These differ in the positioning of the transmitter and receiver and are shown in figure 2.

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Tab. 1: Overview of the methods for structural health monitoring with advantages and disadvantages

NDT technique	Advantages	Disadvantages
Acoustic emission measurement	Monitoring during operation [5, 8]	Multiple sensors are required to increase accuracy [5, 9]
	For large areas [8]	Bad quantitation, difficult interpretation [5, 8]
	Wide frequency range [5]	Noise [5, 8]
	Detect small damages [5, 10]	Unsuitable for offshore WTBs [5]
	Online monitoring [11]	High costs [11]
Acoustic based measurement	Detect damage and severity [5]	Signal processing algorithms required to extract ambient noise [5]
	Requires only a few sensors [5]	Not detectable for damage where the sound energy stays the same [5]
	Monitoring during operation [5]	
	For large areas [5]	
Ultrasonic measurement	High sensitivity and reliability [5]	Signal processing algorithms required to extract ambient noise [5]
	For large areas [5]	Time required for large areas [5]
	Detect the damaged areas [5]	Sensitive to noise [5]
	Online monitoring [11]	Sensors contact surface [5]
	Removal of ice accumulations [12]	High costs [11]
Strain measurement	Monitoring during operation [5, 11]	Many sensors are required for global measurements and to increase accuracy [5]
	High sensitivity [5, 11]	Sensors contact surface [5]
	Mature technique [5, 9]	Positioning of the sensors must be known [5]
	Real-time measurement possible [5]	Temperature influence on the measurement [5]
	Insensitive to electromagnetic interference [5]	
	Online monitoring [11]	
Vibration measurement	Mature technique with high reliability [5]	Many sensors are required to detect damage locations and severity [5]
	Easy installation [5]	Difficult to detect early stages of damage [5]
	Detect damage location and severity [5]	
	Online monitoring [11]	
Thermographic measurement	Non-contact installation [5, 8]	Influenced by temperature fluctuations [5]
	Visual inspection with short time consumption [5, 8]	Difficult to detect early stages of damage [5]
	Drones can be used [5]	Requires a high resolution [5]
	For large areas [5, 8]	High costs [11]
Visual inspection	Low costs [8]	digital cameras required [8]
	Visual inspection with short time consumption [5, 8]	Better results through good image processing software [5]
	Drones can be used	time consuming [8]
	Low costs [11]	
Radioscopy and radiography testing	Non-contact measurement [8]	Instruments for scanning required [8]
	High resolution [8]	X-Ray hazards [8]
Eddy current testing	Non-contact measurement possible [8]	Instruments for scanning required [8]

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Ultrasonic waves are emitted by a transmitter, penetrate the material and are reflected back to a receiver. The condition of the structure can be determined by analyzing the incoming signals. Transmission, attenuation, reflection and resonance all have an impact on the detection of damage to WTBs. [5]

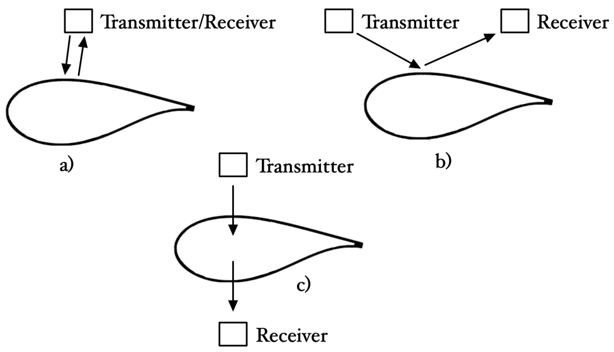

Fig. 2: Three transmitter-receiver settlements used in ultrasonic inspection: a) pulse-echo, b) pitch-catch, c) through-transmission (own illustration based on [16])

A special type of ultrasonic measurement is the measurement using guided waves. In contrast to conventional ultrasonic measurement, the ultrasonic waves expand along the structure and are guided by the structure boundaries. In order to use guided waves for damage detection, the healthy condition of the structure must be known in advance so that it can be used as a reference. [7]

Currently, the procedure is mostly based on the pulse-echo or pitch-catch approach [8]. The difference between conventional ultrasonic measurement and ultrasonic measurement with guided waves is simplified illustrated in figure 3. The precision of ultrasonic measurement is around 1 cm [11].

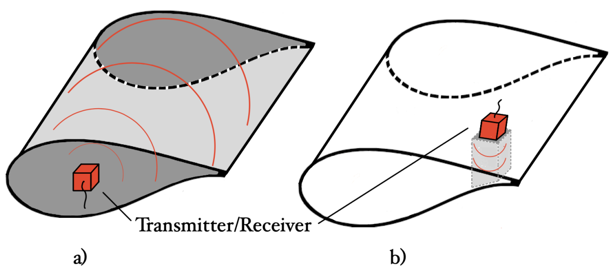

Fig. 3: The difference between a) ultrasonic guided wave measurement and b) conventional ultrasonic measurement

In a study conducted by [12], it was found that the guided ultrasonic waves are also suitable for preventing or removing ice build-up on the WTB by exciting the material particles.

5.4 Strain measurement

For strain measurement, strain sensors are attached to the surface of the WTBs or incorporated into the material to detect compressive and tensile stresses. In order to monitor the local strain continuously, the position of the sensor must be known. Strain gauges or fiber optic sensors are often used. Fiber optic sensors are currently used because they do not require an external energy source. [5]

Strain measurement can be divided into two types [5]:

- direct strain and
- shear strain.

The difference is illustrated in figure 4. The precision of this method is around 1 cm [11].

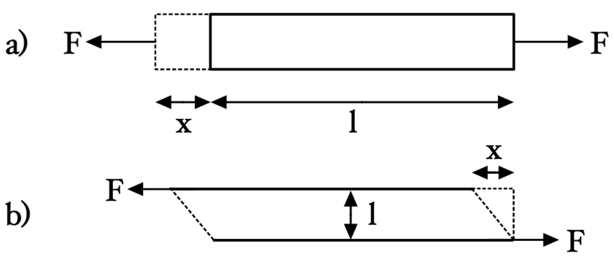

Fig. 4: The difference between a) direct strain and b) shear strain (own illustration based on [17])

5.5 Vibration measurement

Vibrations caused by rotating WTBs are the main cause of wind turbine failure [18]. Vibration analysis can be used to detect damage at an early stage. Damage leads to changes in the material properties of the WTBs. The approach is based on recognizing the change in physical properties through modal characteristics. The parameters which are affected are mass, consistency and damping. [5]

Wind turbines are exposed to wind currents and turbulence, which cause vibrations in the WTBs. Depending on the level of damage, the vibration signals contain different signatures. These are identified using signal processing techniques (time-based, frequency-based, time-frequency-based). [7]

Sensors are used to record the vibration signals. Due to the damping, several vibration sensors are required to identify fault locations. Currently, research is focusing on improving signal processing techniques, for example by integrating them with machine learning tools. [5]

During a 3.5-month test phase on a WTB in operation, [19] detected damage larger than 15 cm using the vibration-based approach.

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5.6 Thermographic measurement

Temperature measurement is used to detect delamination and impact damage. The damage can be detected on the surface as well as in the substrate using this method. [5]

The method for detecting temperature changes is divided into the **passive monitoring method**, in which the ambient temperature is compared with the material temperature and the **active monitoring method**, which is based on the change in the material temperature due to different loads. Passive methods are rarely used in the monitoring of WTBs. The active method is used more often. This requires an external excitation source, such as heat lamps. The transferred energy leads to specific temperature distributions around the damage and thus enables detection. Internal damage such as cracks in the matrix or the pull-out of fibers can also be detected by thermographic measurement. This thermal imaging technology is not suitable for use during operation, because it is heavily dependent on the ambient temperature. [7]

Thermographic measurement can achieve an accuracy of 3-5 mm [11]. [20] have developed a continuous laser thermography method with an algorithm that detects internal delamination on WTBs. The method was successfully verified by an experiment using a WTB with internal damage of 20 mm. Further studies are required for practical use in order to increase the inspection speed.

5.7 Visual inspection

This method is used to detect damage to the surface such as cracks or scratches. Historically, this method is based on the principle of the "naked eye". [7]

Today, image processing systems are used, which include recording devices, computers and image processing algorithms. The method can be used to determine vibration behavior, structural stresses or strains and defects. It is suitable for measuring WTBs because it can capture large areas in a short time. [5]

5.8 Radioscopy and radiography testing

The x-ray imaging technique is based on the nonuniform absorption of x-rays of the damaged area. This method can be used to localize internal damage. An x-ray source and an x-ray detector are required. X-ray sources are often x-ray tubes with a low photon flux. x-ray film is widely used as the x-ray detector. The method is used more for checking the quality of WTBs and not for use during operation. [7]

5.9 Eddy current testing

Eddy current testing is based on the change in the conductivity of the material as a result of damage. Electromagnetic eddy currents are induced in the material. Measuring the high-frequency eddy currents allows conclusions to be drawn about the conductivity. If there is damage, the eddy current density changes and uneven heating occurs, which can be recorded using an infrared camera. The method is also suitable for composite materials. [7]

6 Results

Strain measurement and vibration measurement are two of the methods that have already been established for SHM of WTBs. However, these methods do not only have advantages. For this reason, other methods for SHM have been tested in the past and still offer further potential for research. One reason for researching new techniques is the high demand of sensors for strain measurement or vibration measurement. By using other techniques, the number of required sensors can be reduced without compromising the measurement accuracy and still enabling an area-wide measurement. Methods such as acoustic (emission) measurement or ultrasonic measurement are already widely used. Eddy current testing and radioscopy tend to be the exception. Measures whose data is available online are suitable for SHM. The measurement takes place continuously and during operation.

7 Discussion

With regard to continuous monitoring of the WTBs, SHM measures that can continuously evaluate data in real-time are of particular interest. Measures that cannot be used during operation and therefore do not enable real-time recording should be used as a supplement to increase the accuracy of the monitoring. The research has shown that no method has a unique position in the field of SHM. Rather, it will depend on the boundary conditions as to which method is suitable for the application. However, it can be assumed that strain measurement, acoustic (emission) measurement, ultrasonic measurement and vibration measurement methods in particular will continue to be important in the future, because these methods are already widely used and continue to offer significant scope for research.

The identified techniques provide a good overview of the possibilities for SHM. However, the individual methods can be specifically individualized, for example by using different sensors. The described advantages and disadvantages then apply generally to the method and it must be verified whether advantages and/or disadvantages can be eliminated or

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supplemented by different configurations. It would also be possible to combine different methods to improve the measurements. For example, acoustic emission measurement could be combined with ultrasonic measurement. Ultrasonic measurement can be used to determine the shape and size of the damage. The acoustic emission measurement is then used to localize the damage. In the field, it is necessary to check which process can be used for which material.

8 Outlook

As the study has shown, there will be a need for further research in the field of SHM of WTBs in the future. No method is so mature and fully researched that there is no longer any need for optimization. The following points are particularly relevant:

- Minimizing the number of sensors with the same or better measurement quality
- Reduction of noise to improve measurement quality
- Use of artificial intelligence to detect damage patterns
- General improvement of the sensors and signal processing algorithms

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