Damage detection in turbine wind blades by vibration based methods

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Abstract. The paper describes results of numerical simulation for damage localization in the composite coat of a wind turbine blade using modal parameters and a modern damage detection method (wavelet transform). The presented results were obtained in the first period of research on the diagnostic method, which is aimed at detecting damage in the blades of large wind turbines during normal operation. A blade-modelling process including the geometry, loads and failures has been introduced in the paper. A series of simulations has been carried out for different localizations and size of damage for finding the method's limits. To verify the results of numeric simulations a subscale blade has been built which has geometric features and mechanical properties similar to the computer model.

1. Introduction

The object of this research was the blade of a Horizontal Axial Wind Turbine, which is the most important sub-assembly of such a power plant. Nowadays, the blades are made of glass- or carbon fibres composite that are characterized by relatively small weight and higher strength compared with metallic structures. Employment of that new material technology makes possible building larger and more effective turbines. But such constructions are more exposed to the different kind of breakdowns and the continuous character of their operation causes that the blades are unceasingly loaded in different directions. Owing to real-time condition monitoring of all turbine elements it is possible to detect early an appearing damage. In modern constructions the diagnostic system is an the integral part of the structure. That makes it possible to create favourable conditions for failure-free operation in a set-up time. The most dangerous of composites failures are those which destroy the structure of the material. There are no external symptoms on the element surface, which makes damages very difficult to detect. Because of that, intensive work is conducted to create efficient methods of fault detection and localization but most of them require stopping the rotor.

Paper [1] presents results of fatigue tests of full-scale blades. The Authors have noticed connections between characteristic features of the emitted acoustic signal and mechanical properties (vibrations, modulus of elasticity and tip bending), changes of which can indicate the appearance of damage. Also paper [2] describes the application of acoustic emission for damage detection. Analysis
of signals from sensors located on a blade surface allowed detection of existing defects and active zones where risk of damage was apparent. Descriptions of acoustic signal analysis of blades for diagnostics are also given in [3][4][5][6].

Ultrasonic computer scanning is utilized in [7] for damage detection. The method made use of a movable transmitter and a stationary receiver for creating a defects map of the tested surface. Also paper [8] describes the application of ultrasonic method for non-destructive testing. However, this technique is very time-consuming.

The presented approaches require specified conditions of measurement (restraint the blade, install complicated measuring equipment, apply a static load). The techniques which are free from those disadvantages are proposed in [9][10][11]. An infrared digital camera was used to find temperature changes of the blade surface. It has been shown that the method effectively indicates cracks as well as places threatened by damage.

The basic assumption of vibration damage detection is that vibration parameters such as natural frequencies, displacement, mode shapes or damping depend on the physical properties of the structure. For example, a method based on analysis of the transmittance function is presented in [12]. Results of the investigation presented in [13][14] determine that composite damage changed the vibration spectrum of the structure, which allowed creating a non-destructive testing method of the blade during normal running. Damages may significantly reduce the stiffness of the structure. In paper [15] global modal methods were used (mainly at low frequency). Signals from sensors of strain and acceleration were analyzed to determine a stiffness change of the tested element. Paper [16] shows that simple measurements and appropriate analysis techniques of mode shape make it possible to detect the damage. Wavelet transforms are used to analyze the mode shapes of the damaged plate and beam. That is why this technique was applied in this experiment.

2. Theoretical background

Analysing a signal in different frequency bands with different resolution by decomposing it into a coarse approximation and detailed information we call a wavelet transform [17]. The wavelet (means a small wave) is a kind of mathematical function used to divide a given function into different frequency components and study each component with a resolution that matches its scale. The wavelets are scaled and translated copies of a finite-length or fast-decaying oscillating waveform ("mother wavelet"). The shapes of exemplary mother wavelets are presented in figure 1.

![Wavelet Shapes](image)

Figure 1. Shape of exemplary mother wavelet: a) haar; b) mexican hat; c) gaus4; d) morlet.

The width of the window is changed as the transform is computed for every single spectral component, which is probably the most significant characteristic of the wavelet transform. Wavelets are well-suited for representing functions that have discontinuities and sharp peaks, and for accurately deconstructing and reconstructing finite, non-periodic and/or non-stationary signals. Wavelet transforms can be used to represent continuous-time (analog) signals. We classified them into discrete wavelet transforms (DWTs) and continuous wavelet transforms (CWTs). CWTs operate over every possible scale and translation. The DWTs use a specific subset of scale and translation values or representation grid. For more detailed information please follow the literature [17][18].
3. Numerical calculation
The tested blade has 1.74 meter length, without the twist of profile and one longitudinal spar. Glass fibre and epoxy resin have been used as the laminate components on the structure material. Reinforced fibres have been symmetrically arranged (45º/-45º). A changing thickness of the blade coating has been assumed. The blade was divided into three sections which had a different number of laminate layers. The total mass of the blade was about 2kg. Mechanical properties of the composite are presented in table 1. The geometrical characteristics of the blade are presented in table 2.

| Table 1: Properties of composite material components. | Table 2: Geometrical features of the blade. |
|-----------------------------------------------------|------------------------------------------|
| Epoxy resin | Glass fiber | Dimension [mm] |
| Young modulus, E | 3.43 GPa | 66.5 GPa | Total length | 1740 |
| Poisson ratio, ν | 0.35 | 0.23 | Max width | 160 |
| Kirchoff modulus, G | 1.27 GPa | 27 GPa | Tip width | 32 |
| density, ρ | 1250 kg/m³ | 2250 kg/m³ | Thickness of spar | 2.0 |
| Thickness of section 1 (near blade root) | 2.0 |
| Thickness of section 2 (middle part of blade) | 1.5 |
| Thickness of section 3 (near blade tip) | 1.0 |

In the FEM modelling process the isoparametric shell element has been applied, which has eight nodes and six degrees of freedom at each node. A series of simulations was conducted. At first, the Block Lanchos method has been used to calculate the natural frequencies of the undamaged blade. In the next step, the damage has been applied to the composite coat. The crack has 2 mm width and four values of length (from 5% to 30% of the blade width) and for three localizations of the damage. All simulations and calculations have been conducted using applications of ANSYS and MATLAB® Software. The blade model and the place with damage is presented in figure 2.

![Figure 2. Blade model with the damage (red line).](image)

4. Experimental measurements
A real blade (similar to the computer model) has been built to verify the results of simulation. The object was fixed on a special steel table which guarantees high stiffness and isolates from external sources of vibrations. An electromechanical shaker (GWV B100) has been used for vibration
excitation (figure 3a). Measurements of vibrations have been carried out using a PSV-400 Laser Scanning Vibrometer (figure 3b). The main advantages of a Laser Doppler vibrometer are automation, high sensitivity and non-contact capabilities [19]. Thanks to the sensor head with a laser Doppler vibrometer which enabled fast, accurate and non-contact vibration measurements of the whole surface, the influence of undesirable effects which could distort the results has been eliminated.

Figure 3. Experimental setup: a) shaker – 1; blade – 2; b) laser vibrometer – 3; c) model of damage.

The mode shapes of the object have been determined by velocity measurement for the undamaged and damaged blade. Damage has been applied in the form of an additional mass fixed to the surface of the object (figure 3.c). Measurements have been carried out for three values of additional mass and several localizations. All damage cases are gathered in table 3. The scan grid of measurement points is presented in figure 4. There are 290 scan points (5 lines, 58 points per line) for the first and second series of measurements. The last series has been carried out with one line (211 scan points). Each point has been excited with frequencies sweeping from 4 Hz to 250 Hz with a resolution of 0.1 Hz (7 mode shapes).

| Value of additional mass (percent of total mass) | Number of scan points (per line) | Number of damage localization |
|-------------------------------------------------|---------------------------------|------------------------------|
| 12%                                              | 58                              | 3                            |
| 6%                                               | 58                              | 3                            |
| 2%                                               | 211                             | 7                            |

Figure 4. Research object and measurement grid.
5. Results
The first and seventh bending mode shape form experiments are presented in figure 5. As can be noticed, the signals for an undamaged and damaged blade differ from each other. Wavelet analysis was carried for one line localized at half of the blade width. Only bending of the form of mode shape was taken into account. Continuous wavelet transformation has been performed for each measured mode shape line. The signal from measurements has been denoised additionally. The difference between the undamaged state and the mode shape line for damaged blade has been calculated and transformed with the ‘gaus4’ mother wavelet. Figure 6.a,b,c presents three exemplary results obtained for different localization of damage (12% of total mass).

![Figure 5](image1.png)

**Figure 5.** Example of measurements results. Comparison of measurement lines for undamaged (solid line) and damaged (dashed line): (a) mode II, (b) mode VII.

![Figure 6](image2.png)

**Figure 6.** a), b), c) Results of CWT for three damage localizations;

The graphs show the maximal values of decomposition coefficients for growing decomposition level. The vertical line on the graph shows the real positions of damage. For all cases it can be noticed that the location of damage has been acceptably indicated.

Figure 7a,b shows the first and seventh bending mode shape from computer simulation. The CWT analysis was carried out for one line localized along the spar (136 points).
Analysis of simulation results has shown that it is possible to define places of local rigidity changes. Unfortunately, in the case when those changes come/follow from the structure (e.g. change of element thickness – figure 8) it is impossible to detect and localize the damage without acquaintance of the initial/base state. Exemplary results of CWT analyses for the first mode shape and three cases of damage location are presented in figure 9.

Figure. 7. Example of simulation results: (a) mode II, (b) mode VII.

Figure. 8: Results of CWT for first mode shape: a) undamaged blade; b) damaged blade (30% width of blade).

Figure. 9: a), b), c) CWT results for three damage localisations (difference between the undamaged and damaged state) – black vertical line marked the position of the damage.
6. Conclusions
A method for damage localization in the composite blade of a wind turbine based on one-dimensional continuous wavelet analysis applied to mode shapes is presented. The mode shapes are determined by experiment and simulation. The experiments were conducted using a laser vibrometer. The Gaussian wavelet with different decomposition levels has been used as mother wavelet. The analysis of all damage cases has shown that localization of a relatively small damage is possible. The results obtained will allow to build a numerical model of a full-scale blade taking the advanced composite structure and service loads into consideration. A method of damage detection (cracks and delamination) will be created for this blade.

The trend of further research on this method will be concentrated on:

- improving the blade model for elimination of violent jump of coat thickness with simultaneous preservation of the character of decreasing thickness;
- increasing the sensitivity (analysis of higher frequency mode shapes and forced vibration);
- computer simulation of full-scale blade under service load;
- experimental measurements of blade with damage (crack);
- improving the measurement methodology (choice of measurement place and density of grid).

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