STRUCTURAL HEALTH MONITORING OF WIND TURBINE
BLADES USING DIFFERENT NONDESTRUCTIVE TESTING
METHODS

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Abstract

The most important part of wind turbine is the blade that must be tested during the fabrication and during the functioning when can be damaged by moisture absorption, fatigue, wind gusts or lightning strikes. The common defects in turbine blades may be faulty microscopic and mesoscopic appeared in matrix, broken fibers can also appear and develop under moderated loads, or cracks and delaminations due to low energy impacts, etc. The paper propose to present the some results obtained from testing of glass fiber reinforced plastic used in the construction of the wind turbine blades as well as the monitoring of the entire scalable blade using different sensors placed on critical location on blade. The sensors are placed on critical location on blade determined by finite element method simulation and a comparison between the complementary methods is done.

Keywords: wind turbine blades, structural health monitoring (SHM), nondestructive testing, sensors

1. Introduction

The problem of climate changing, due to pollution includes not only modification of average temperatures but also changing of its different aspects as wind types, quantity and precipitation types, types and frequency of extreme meteorological events. EU studies the possibility to update air pollution standards for thermal power station based on coal, in the conditions in which this type of installation represent the biggest source of sulfur dioxide and mercury, nitrogen oxides, arsenic, lead and cadmium emissions. Thus, the market for electrical energy obtained by harvesting wind power is expanding [1]. In Romania over 3% from annual electricity is produced by wind turbines, the majority being GE1.5dle or similar, having the length of the blade of 33.5m and the height of tower of 65/80m [2]. In January 1st, 2017, Romania recorded 3025MW installed wind turbines, the total number of installed turbines being 1250 at an average turbine power of 2.5MW (located in 80 wind farms in operation, the average of a wind farm in Romania being 40MW) [3].

Wind Turbine (WT) spreading and increasing of capacity are important ways to respond to growing global energy demand. In order to obtain greater efficiency and to increase the generated power, the general trend is the use of large-diameter rotors, manufacturing the blades with glass fiber-reinforced plastics (GFRP) due to their low weight. This resulted in WT blades length of 60 m [4]. The blades are usually subject to random and complex mechanical stresses. The most common defects in turbine blades may be faulty microscopic and mesoscopic
appeared in matrix, no detected by classical nondestructive testing (i.e. using phased array sensors), broken fibers can also appear and develop under moderated loads, or cracks and delaminations due to low energy impacts, etc. However, large blades led to no concrete data in due time during in-service inspection. These explain the attention given to structural health monitoring (SHM) [5] systems for wind turbine blades (WTB), development and consolidation of diagnosis, prognosis methodologies, damage detection (location and their nature). The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an arrangement of sensors, the extraction of damage-sensitive features from these features to determine the current state of system health [6]. Figure 1 illustrate the SHM system concept [5], the blades damages shall be detected and evaluated with high probability of detection and reliability coefficient.

Figure 1. SHM system

For an estimated lifetime of 20 years and extended as long as is possible, the long-term integrity of a blade became a very interested area. The monitoring of WTB made from GFRP have been reviewed in [4], proposing either statistical pattern recognition using simulation or experimental data, or in [7] considering mechanical property testing and full-scale testing as well as nondestructive testing methods. In order to calculate the lifetime of GFRP structures used in WTB construction, it is essential to have access to information about fatigue resistance of the material. These data include a number of fatigue tests in the frame of specific combinations of amplitude and average stress.

Different databases were compiled, regarding extended fatigue of GFRP in WTB [8], [9], the results between different materials and the loading conditions are not transferable, being necessarily further high experimental effort for each new project and used material. There are many literature reviews concerning WTB starting from design, propulsion and including theories of maximum efficiency [10-13]. The nondestructive testing (NDT) techniques for in-service inspection and determination of regions with high degradation risks are developed (function on the type and the size of the WT) [14]. In order to decrease the fabrication and maintenance costs, as well as for avoiding unproductive time, NDT is required both during fabrication and in-service.

The paper presents some results of testing of a WTB, in static conditions, using different type of sensors (i.e. wireless sensor (WRS), optical fiber (OF) Fiber Bragg Gratings (FBG), stress/strain gauge, noncontact ultrasound, not only these) in order to monitor possible damages that further can be transformed into flaws. The results of complex mechanical tests, effected on scalable WTB models (in our case a blade of 1750mm length) are used to give efficiency to monitoring strategy. To determine the righteous of solutions, a scalable WTB has been
constructed, that had the scaled dynamics of a full-scale blade as well as enough sensors for measurements as well as monitoring. The maximum stress zones [15] and damage evolution and remnant stress [16] have been determined using Finite Element Modelling (FEM).

2. SHM based on sensors, experimental set-up

WTBs are most exposed component of WT. The composite structures are designed and realized based on the concept that a layered structure more easily supports an early stage damage that can be stopped when it has a tendency to propagate following the repeated loads prescribed by the project. Detecting early-stage WTB degradations and monitoring their progress over time can lead to improved diagnostic capability and the development of more efficient repair strategies and, last but not least, the improvement of structural blade design. Taking into account the efficacy of the method and \textit{a priori} knowledge about WTB (obtained by simulations), the sensors are distributed on the most expected damage area, aiming the minimizing of the sensors number (Figure 2).

The blade has been realized from E-glass/epoxy EPIKOTE Resin MGS LR 385 composite. The leading edge is straight and the trailing edge conical for an easy construction. The profile follows NACA airfoil. For increased structural strength and stiffness at 0.286R (R- the total length of distance between the center of rotor and the tip of blade), the same NACA has been applied both for the upper surface and lower surface, keeping the aerodynamically performances of the blade’s tip. The profiles between 0.268R and tip were linear interpolated. A compromise has to be found between high-resolution and long propagation distance. The results are obtained at preliminarily testing of a scalable WTB, in laboratory, using passive radiofrequency identification (RFID) wireless sensor (WRS) as uni-dimensional displacements sensor, optical fiber (OF) FBG sensor technology and stress/strain gauge (SG).

The passive WRS designed to monitory stress/strain status have as sensitive element, that follows the relative displacement (compression or tension) of its components due to an impact and can develop slows or either fast. The sensor consists of a folded rectangular microstrip patch antenna [17] coupled with a tunable inductive SRR and with a passive IC chip.
The structure of this type of sensor is shown in Figure 3a, the sensing element is shown in Figure 3b.

In specific construction as 2D geometry on flexible support, copper SRR can be used as stress/strain sensors [18], [19]. Resonance frequency of sensor is in range of RF and microwaves, depends of geometrical dimensions and design, for a quality factor of the equivalent circuit between tens - hundreds. WRS [20] presents resonant properties [21] and the inductance and the capacitance are given by [22]. The resonance frequency is 

$$f_r = \frac{c}{4(L + \Delta L)\sqrt{\varepsilon_r}}$$

with $c$ speed of light in vacuum, $L$ the length of the copper layer, $\varepsilon_r$ the dielectric permittivity of the substrate, $\Delta L$ is the additional length who compensate the effect due to thickness, width and dielectric constant of the substrate. Parallel with capacitance $C$, a capacitive element sensitive to stress/strain is connected, with the capacitance varying linear with the strain as 

$$C_{\text{sensitive}} = \varepsilon_r\varepsilon_0 w_1 g/u(1+\varepsilon_s)$$

with $u$ thickness of dielectric layer and $\varepsilon_s$ strain in $\mu$m/m. For the capacitive element, sensitive to stress/strain, to function upon a law closer to this, it is imposed that the Poisson ratio of dielectric support shall be as high as possible. For polyimide, the layer supporting copper strips, the Poisson ratio is 0.4. If $\varepsilon_s=10 \mu$m/m, the connection between the two capacitance make $C$ increases with 10%, inductance $L$ remaining unchanged. Detection system consist in a RFID reader and a RFID tag [22], the tag including the sensor and the integrate circuit (IC). When the sensor detect a modification of the strain $\varepsilon$, the frequency is

$$f_r' = \frac{c}{4(1+\varepsilon)(L + \Delta L)\sqrt{\varepsilon_r}} = \frac{f_r}{1+\varepsilon} \approx f_r(1-\varepsilon)$$

(1)

For a load small, the resonance frequency modifies almost linear with load, the load can be determined if the resonance frequency is measured. The RFID tag antenna assures that the interrogation frequency $f$ shall be equal with the one of RFID tag to obtain perfect matching of impedance between antenna tag and IC chip. The smallest amount of energy must be transmitted toward reader to activate RFID tag, the transmitted power threshold (measured through the reader) reach minimum value at resonance frequency.

Optical fiber (OF) sensors are made based on OF in integrated structures. SHM includes the use of OF for detecting delamination in composite laminates [23] and monitor impact event occurrence [24], [25]. This sensor can monitores the structure in critical regions. The central wavelength of this signal, called Bragg wavelength $\lambda_B$ is related to the physical parameters of the grating according to 

$$\lambda_B = 2nA$$

where $n$ is the effective refractive index of the fundamental mode propagating inside the fiber, $A$ is the spacing between gratings, known as grating period. When the fiber containing OF is submitted to strain, the central wavelength
is displaced to higher or smaller values [26]. The direction and the magnitude of displacement is proportional with the modification of strain or temperature. The strain axial sensitivity is 
\[ \frac{d \lambda_y}{d \varepsilon} = \lambda_y (1 - p_e) \]  
where \( \lambda_y \) is the OF wavelength shift; \( \varepsilon \ll 1 \), \( p_e \) is photo-elastic coefficient of the fiber \( p_e = 0.22 \), OF sensors whose gauge lengths are about 10mm were used for SHM.

\[ \frac{\partial \lambda_y}{\lambda_y} \approx -(1 - p_e) \varepsilon ; \quad \frac{\partial \lambda_y}{\lambda_y} = 0.78 \varepsilon \]

The OF strain sensing can be expressed as 
\[ \varepsilon = \frac{1}{0.78 \times 10^{-6}} \frac{\Delta \lambda_y}{\lambda_y} \]  
In structure of WTB, 3 OF were embedded along the central longitude of the blade, placed into critical points determined by FEM of blade under bending.

3 sensors C2A-06-062WW-350, stacked rosette were used, each having 3 strain gauges with 350 \( \Omega \) electrical resistance were employed (Figure 4a). These were connected to Vishay P3 Strain Indicator and Recorder (Figure 4b), in quarter bridge connection with automatic balance.

Their positioning (Figure 4c) has allowed the determination of deformations due to bending along blade axis at distance of 488 mm from the fixed end, respectively closely to trailing edge at 409 mm from the fixed end, as well as closely to the leading edge at 351 mm from the hub. The bending test were effectuated in 7 loading stages with 100 N steps, with maximum of bending momentum of 900900 Nmm.

### 3. Experimental results

The simulation of blade behavior has been carried out with ANSYS Academic 17.2. at 300 mm distance from the tip of the blade, a compression force of 500 N has been applied on Y axis (blade upper shell) on 100 mm width surface, producing a displacement of the tip of 30.082 mm. Figure 5a presents the division of the blade in critical regions, in Figure 5b is presented the loading forces disposition. The FEM model shown above takes into account the presence of the reinforcement structure, who’s mass cannot be neglected, especially if one considers that the distance from the axis of rotation increase the inertia and can reduce the frequency associated with the first mode of vibration of WTB. Fortunately, the glass fibers employed makes the structure very rigid. OF sensors are placed in region at 307 mm, 362 mm, 406 mm from the hub fixing in stand. All the loadings are static and the sensors were placed in region with maximum critical points. For establishing critical regions of WTB using FEM, 1338842 nodes, 832563 elements were employed, the maximum dimension of an element being 8 mm.
The resulted maximum stresses were under material flow limit. In all the cases, the stresses on lower shell are higher than on the upper shell. The maximum stresses on WTB appear closely to the joint between the hub and the longeron and at transition between circular geometry to NACA profile.

For the WRS the reader antenna (Figure 2) is fixed on the upper part of the stand, at 30 cm from the middle area of WRS placement locus. The antenna is connected to a logger reader coupled to PC by USB. IC frequency range is [840 ÷ 960] MHz. The results of bending tests in a loading-unloading cycle are presented in Figure 6 a and b.

Maximum deformations at 700N loadings are characteristics of region where sensor S1 is placed (along longeron axis) and the minimums are in the region of sensor S2 (placed outside the critical zone). In addition, the deformation is linear, the loading remain in elastic range. During the unloading, the values follow the same characteristic as at loading. Comparing loading/unloading data at 500 N with the simulated ones, it can be observed a good correlation of the displacement, experimentally being determined as 37 mm.

The OF sensor FBG single DTG S-01 used for monitoring composite materials type GFRP [27] have center wavelength in 1535 nm with strain sensitivity 7.8x10⁻⁷ µε⁻¹ and temperature sensitivity 6.5x10⁻⁶K⁻¹. This is connected at optical system Spectral Eye 600 coupled with PC. During the experiments, the temperature has been maintained constant at 22±1°C.
The experimental test setup was performed according to [28] upon sufficient drying; progressively loading/unloaded forces were applied. Physically, stress concentration around the damage in the composite laminates can be directly observed from row sensor signal. The data processing has been made in Matlab 2014b, the temperature correction being made, the equipment indicating the temperature of fiber, too.

Figure 7. FBG measurements: a) response to successive loading; b) relative variation of Bragg wavelength Daca am alt grafic pana la conf se schimba

Figure 7a presents the raw data recorded by the device for different loadings. The relative variation of Bragg wavelength was determined in function of loading is presented in Figure 7b showing that the relative variation of Bragg wavelength is linear. The dependency strain-load for WTB in a loading-unloading cycle for three sets of experimental measurement is presented in Figure 7. The same linear dependency strain-load can be shown, even the existence of a remnant stress at force removal, indicating an accumulation of energy in WTB composite structure, preponderant in the resin. The measurements using OF were carried on the same time with those using WRS sensors.

The sensor denoted T1 measures the deformations of the blade in the palne of I shape longeron, having heigth/width variable along the blade, T2 measures the deformations of blade shell closedly to the trailing edge and T3 measures the deformations of blade shell closedly to leading edge. The experimental data were used to calculate [29] maximum specific deformation $\varepsilon_{\text{max}}$, minimum specific deformations $\varepsilon_{\text{min}}$, acute angle from the axis $\theta$, the maximum shear strain $\gamma_{\text{max}}$, maximum normal stress $\sigma_{\text{max}}$, minimal normal stress $\sigma_{\text{min}}$ and tangential maximum stress $\tau_{\text{max}}$. Figure 8 presents the plotting of $\sigma_{\text{max}}$, $\sigma_{\text{min}}$ and $\tau_{\text{max}}$ for the 3SG for loading (Figures 8 a,c,e) and unloading (Figures 8 b,d,f) until maximum force of 700N.
It can be observed that the high values of stresses with applied force appears in the region where sensor T3 is placed, this region being emphasized in FEM analysis too. The plots following the same profile shows that the tests were carried out in elasting range.

4. Conclusions

Monitoring of complex structures has become an economic necessity, the trend consisting in using of a lot of sensors (described in this paper, i.e. not only) to detect broken fibers which may occur and develop under moderated loads, or cracks and delaminations due to low energy impacts, etc. Practical applications demonstrates that, in order to avoid environmental disasters, it is necessary to establish diagnosis and prognosis methods, based on using information obtained from sensors constructed on known physical principles. The monitoring is close related with nondestructive evaluation and the trend is to obtain real time information. Scalable WTB have been constructed and tested to loadings using WRS, OF FBG and SG located in the maximum concentration stress zones. The tests were carried on scalable models, in the further research the WRS sensors will be embedded, because in the frame of the project that sustains the paper, the blades will be employed into a demonstrator to show the righteous of solutions, reliability of correct diagnosis probability, prognosis, and evaluation of residual lifetime and maintenance management.

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