Structural health monitoring of critical zones of small wind turbine blades for domestic users

A Savin1,*, N Iftimie1, S M Nastac2 and M D Stanciu3
1 National Institute of Research and Development for Technical Physics, NDT Department, 47 Mangeron Dimitrie Boulevard, 700050, Iasi, Romania
2 Dunarea de Jos University of Galati, Engineering and Agronomy Faculty, Romania
3 Transilvania University of Brasov, Mechanical Engineering Department, Brasov, Romania

E-mail: asavin@phys-iasi.ro; mariana.stanciu@unitbv.ro

Abstract. The most important part of wind turbine is the blade that must be tested during fabrication and functioning when can be damaged by moisture absorption, fatigue, wind guests or lightning strikes. The fibers can also appear and develop under modified loads or cracks and delaminating due to the low energy impacts etc. The aim of this paper is to identify the modal behavior of small wind turbine blade in terms of the signal convergence, modal evolutions and frequency spectra. There are numerous methods for monitoring and detecting structural damage of the wind blades, but in this study it was used the impact hammer method. The results emphasized the natural frequencies, the modal shape of structure and the signal coherence captured in different points.

1. Introduction

From references and discussions, it has been found that a major problem related to the depletion of earth’s resources finds the solution in nature by using renewable energy of the wind [1, 2]. In this respect, engineers have designed wind power conversion systems for electricity either to serve the population at regional level (wind farms), or for domestic users or for households in hard-to-reach areas and without electricity. During the operation of the wind turbine, the most exposed destruction is the blades, the nacelle bearings and the tower. The most important part of wind turbine is the blade that must be tested during fabrication and functioning when can be damaged by moisture absorption, fatigue, wind guests or lightning strikes [3, 4]. Being made from composite materials, the wind blade shows outstanding mechanical properties at static and cyclic stresses but the impact damage and interlaminar fissures occur which cannot be detected easy [5, 6]. Numerous methods for monitoring and detecting structural flaws of the blades have been developed such as C-scan or Top view ultrasound [7], Lamb waves Using non-contact transducers [8], with Hertzian contact [9] or compression waves generated by normal transducers. Comparison of the modal analysis of blade or entire system before operation with the modal response during or after operation can offer an important data about structural integrity of wind turbine blade [10]. The paper presents the results obtained from monitoring of a small wind turbine blade using modal analysis by the impact hammer method. This method consists in the excitation of the structure by shock, its response being captured by accelerometers. The output signals were processed with MatLab soft, obtaining the signal convergence, modal evolutions and frequency spectra.
2. The experimental set-up
For this study it was investigated a GE1.5sle wind turbine type, 1:20 scale, made of 5-layers composite of glass fibres fabric and epoxy resin. The blade contains in interior a stiffening profile made of composite material as well as the blade shell.

The identification of the eigenmodes and eigenfrequencies corresponding to the modal bending evolutions along the x-axis was achieved by the impact hammer method, which consists in exciting the structure by shock, its response being captured by accelerometers. In the first stage, a set of measuring points was established and drawn, which is configured as a three-row array (1, 2, 3) and 14 columns (A, B, ..., M, N) equidistant from each other at a distance 100 mm (between columns) as can be seen in figure 1.

Two points have been established for the structure's excitement: at the tip of the blade - point $\alpha$ (located midway between A3-B3 and 50 mm respectively), and to the grip area - the point $\gamma$ (located between M3-N3 at the middle of the segment). In the figure 1, the exiting points are red. Thus, 52 signals were taken for each of the two excitation points.

![Figure 1. Experimental Modal Analysis (EMA).](image)

The experimental stand was built according to the scheme in figure 1, a - b. The wind blade (1) was suspended with spring elements to simulate the free structure (2) and hit with the impact type PCB - 086C04 (3) on the $\alpha$ and $\gamma$ points, successive. The blade response was captured with accelerometers type PCB-CCP-ICP 320C34 and type 356B21 (4) placed successively at the 3-row (1, 2, 3) and 14-column matrix points (A, B, ..., M, N). Received responses were transmitted via the conditioning device (5) to the Dynamic Signal Acquision (6) connected to the laptop (7). The capture and visualization of the signal were achieved through the software developed in LabView, and the graphic data processing was performed with the MatLab program.

3. Results and discussion

3.1. Signal convergences
The convergence chart expresses the correspondence of the modal frequencies for the various measurement points. It is noted that in the low frequency range (10-500 Hz), the experimentally identified modal frequencies are found for most of the measurement points (figure 2). In figure 2, acceleration and force signals, in time and frequency, are shown for the excitation at point $\alpha$ or $\gamma$ (selective graphs - measurement points A1 ..3, H1 ..3).

The position of the excitation point influences quantitatively and qualitatively the convergence diagram: the excitation from point $\gamma$ (located near of hub area) returns its own superior modes as
compared to the excitation from point $\alpha$ (located at the tip of the blade). This is due to the fact that the excitation point $\gamma$ is located in a more rigid area of the blade, as well as the fact that the section of the blade is characterized by maximum inertia moment in that area. Excitation from the $\alpha$ point can simulate the action of the wind compared to the excitation at the point $\gamma$, which simulates both the action of the wind and mechanical vibrations. These diagrams show the accuracy of the measurements and the fact that the modal frequencies identified and marked on the diagram are those corresponding to the modal response of the entire analyzed structure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Acceleration and force signals, in time and frequency: a) measuring point A1, A2, A3 for excitation at point $\alpha$; b) measuring point H1, H2 H3 for excitation at point $\alpha$; c) measuring point A1, A2, A3 for excitation at point $\gamma$; d) measuring point H1, H2 H3 for excitation at point $\gamma$.}
\end{figure}

It is observed in the global analysis of the diagrams that the frequencies 61, 115, 152, 277, 338, 411, 503, 540 Hz corresponding to the excitation in $\alpha$ (figure 3, a), respectively 61, 152, 277, 338, 411 , 503, 613, 698, 756, 799, 851, 872, 961, 991, 1077, 1110, 1544 Hz, corresponding to the excitation in $\gamma$ (figure 3, b) constitute real modal frequencies of the bending structure along the $x$-axis border conditions. The singular frequencies in the convergence charts are modal modalities that belong to other modal evolutions than the bending analysis.

3.2. The modal evolutions

In order to determine modal evolutions, the imaginary part of the frequency transfer function between the excitation signal and the acquired accelerations at each point of the measurement matrix was
evaluated and the results were plotted for each row of the matrix corresponding to the identified modal frequency. It can be noticed that the experimental results present a good correlation with the theoretical estimations in the literature (figure 4).

![Figure 3 Matrix convergence of measurement points: a) corresponding to excitation at α point; b) corresponding to excitation at γ point.](image)

![Figure 4. The modal evolutions (bending modes) corresponding to the 2nd row of measuring points: a) for the excitation α point; b) for the excitation γ point.](image)
In the case of excitation in $\alpha$, three frequencies (61 Hz, 152 Hz, 277 Hz) were found and for the excitation at the point $\gamma$, five modal frequencies were obtained (61 Hz, 152 Hz, 283 Hz, 341 Hz, 421 Hz). When it is excited in $\alpha$ point, the structure response can be noticed through the modal evolution. This modal evolution is similarly with the analytical ones. In case of the structure is excited in $\gamma$ point - placed on opposite part of the blade tip, can be remarked certain asymmetries in modal evolutions (especially for big faults). This can be explained both by the anisotropy of the structure and the geometric asymmetry due to the shape of the aerodynamic profiles and the position of the inner stiffening element. A further explanation is also provided by the eccentric location of the $\gamma$ excitation point, which also drives the torsion modes of the blade.

3.3. Frequency spectra

The amplitudes of the Fourier transforms of the acceleration signals on each row were compared, with a correlation of the modal frequencies in the range of 10 - 600 Hz, which corresponds to the frequency range of the excitation amplitude spectrum (figures 5). For signals with frequencies higher than 600 Hz, especially in the excitation situation at the point $\gamma$, there is a non-homogeneity of the spectral frequency distribution for the 14 measuring points on each string (figure 5). The impulse applied at the $\alpha$ point excite the range of low frequencies (less than 500 Hz) so that in the spectral composition of the acceleration signals, the amplitudes of the modal frequencies in this range are amplified much more than the rest of the modal frequencies. For this reason, by comparing the spectral compositions of the impulse acceleration signals applied in $\alpha$ or $\gamma$, corresponding to the same evaluated column, we find that there is a wider frequency range for the second pulse application case (figure 5). This is explained by the major difference in stiffness between the areas where impulse application points are located.

![Figure 5](image_url) **Figure 5** Frequencies spectra for each measuring point row with excitation at point $\alpha$ and $\gamma$. 


4. Conclusion
The usefulness of the study is to identify the modal frequencies that constitute potential local resonance sources for the wind blade. This will inevitably lead to the local amplification of the deformations under the external dynamic stresses and implicitly to the deterioration of the blade zone. This study highlights the possibility of constant or periodic monitoring of the level of structural and functional degradation of the blade by evaluating the spectral changes identified during the measurements.

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