SHM of Floating Offshore Wind Turbines—Challenges and First Solutions

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ABSTRACT

The paper presents an integrated SHM-system for floater, moorings, tower, nacelle and rotor blades. Its core is based on a multivariate SHM-system for rotor blades with three different measuring techniques accompanied by appropriate signal processing approaches:

- Acoustic Emission (AE) is used for identification of relative small damages at the whole blade, e.g. bursts of fibres, cracks of bonding, hits of hail and the localization of damages.
- Acousto Ultrasonics (AU) provides information about relative small to big damages on the transfer path between emitter and receiver of guided waves (cracks, delamination, damages of the surface).
- Operational Modal Analysis (OMA) gives information about large structural modifications e.g. changes of global stiffness, mass and damping ratios in the whole blade.

The most important feature of an SHM-system, however, is not the sensor network, but the analysis capability and the decision support system reducing and interpreting measured data.

The instrumentation plan of a floating wind turbine off the coast of Spain is presented.

INTRODUCTION – THE CHALLENGES OF FLOATING TURBINES

The very large wind turbines of the future will have 10 MW and more output power and they are situated in an offshore environment. Due to the geographical situation two construction types exist:

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- Fixed bottom wind turbine technology at the continental shelf with limitations of water depth of ≈ 50 m.
- Floating wind turbines in deep water areas with extremely abundant wind resources.

Of the latter type only a few research turbines exist worldwide. Due to the harsh offshore conditions and dynamic wind and sea loads SHM is a must on such floating wind turbines. However, there is no experience available with such complex structures. In a European research project HiPRwind such a floating wind turbine will be monitored. SHM is a main research topic at the floater which will be situated off the coast of Spain.

A very critical issue for very large offshore wind turbines is the structural integrity of the rotor blades [1], tower and floater or the foundation respectively, and their remote maintenance. On the one hand, the wind turbines of the future will be much bigger than today. Especially the rotor blades which will have a length of 90 m and more are very critical. The probability of structural failure is much higher than with smaller blades. Additional to that, the environmental conditions on the sea are very harsh, that means the loads onto blades and tower are much higher, too. On the other hand, the accessibility of an offshore wind turbine is restricted due to sea and weather conditions and the availability of supply vessels. Some challenges of the project are harsh offshore environment, underwater measurements, a very complex floating structure with varying loads and boundary conditions, a rotating system, interaction of the mechanical dynamics of floating turbine with aero-elasticity and control commands, interaction between different structural components, etc. Therefore, integrated structural health and condition monitoring is a prerequisite of complex remote maintenance strategies for structural parts of a wind energy converter. Structural Health Monitoring, condition-dependent and predictive maintenance combined with long-term planning of repair measures is the key to ensuring the economic viability of very large offshore turbines.

Additional to the health monitoring the measurement of the dynamic behaviour of floating wind turbines is of great importance for research purposes.

SHM WIND - A HEALTH MONITORING SYSTEM FOR ROTOR BLADES

To introduce the principles the example of an SHM-system for rotor blades of wind turbines is taken. The development of such an SHM-system was started some years ago in two R&D-projects [2], [3]. Now the system has reached a certain stage of maturity and the transfer of results from research to a product SHM.Blade is planned. At the first stage the upcoming product SHM.Blade will not cover all features mentioned in this contribution which describes the final development stage of the system.

Prerequisite – A Sensor Network with optical Data and Energy Transmission

The intension of SHM Wind is not only to indicate an upcoming damage, but additionally to deliver information about the position of damage and its extent. To monitor local effects in the whole blade a sensor network is necessary covering the whole structure. However, due to the exposure of rotor blades to strokes of lightning copper wires only can be used in the first third of a blade. A solution for this problem is either to use only sensors like fibre bragg gratings, FBG, which means to measure local strains only and to dispense with integral measurement like vibrations or to develop an optical fibre-based energy and data transmission to connect sensor nodes to a grid covering the whole rotor blade.

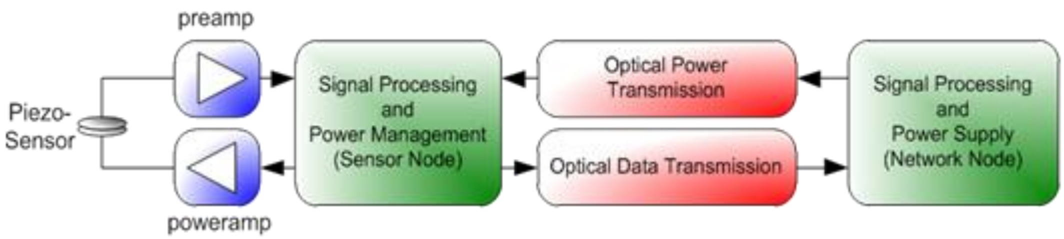

Figure 1. Optical power and data transmission.

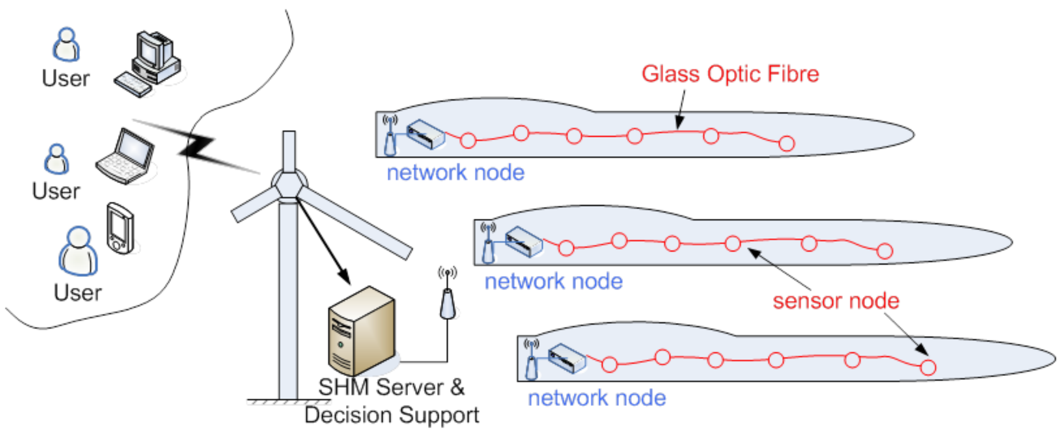

Figure 2. Sensor grid with nodes connected by optical fibres.

SHM Wind is a monitoring system with 3 different measuring techniques consisting of a combination of acoustic emission, acousto ultrasonics and the vibro-mechanic method of operational modal analysis, OMA. While the local monitoring is based on guided elastic waves the global measurement is working with the measurement of accelerations.

Local Monitoring – Active and Passive Guided Elastic Waves

The local monitoring has two different components:

- Acoustic Emission, AE, is a passive technique. Bursts of fibres, cracking of glue and inter-laminar friction cause acoustic emission. The signals are received by piezo transducers. By means of triangulation a localisation of such acoustic events is possible. A summation of acoustic effects over the life time of a rotor blade shows the regions with highest structural changes.

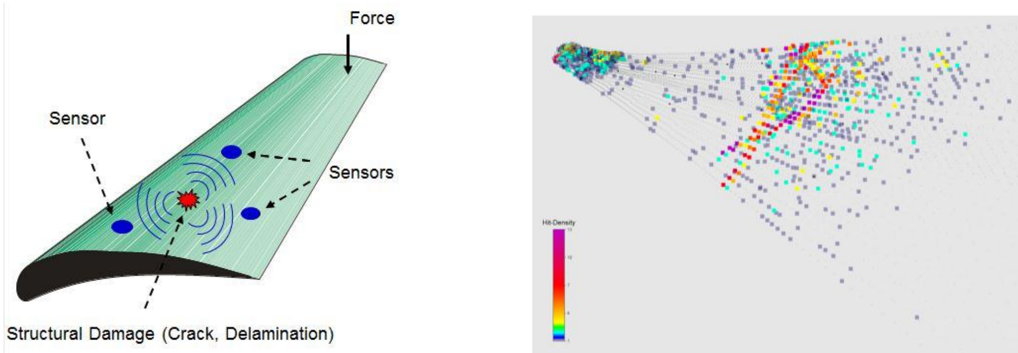

Figure 3. Functional principle of acoustic emission (left); result of a fatigue test of a blade (right).

- Acousto Ultrasonics, AU, as an active principle, using piezo transducer as emitter and receiver of guided waves. When damage occurs between emitter and receiver the transfer-function of the signals will be changed, that means the signal received differs from the one emitted.

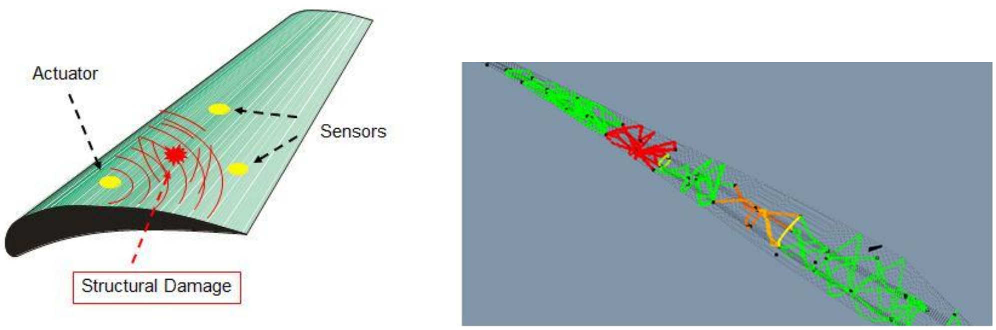

Figure 4. Functional principle of acousto ultrasonics (left); change of transfer-functions between emitter and receiver – red: no correlation between the emitted signal and the one received (right).

Global Monitoring – Operational Modal Analysis

The main task of global monitoring is to keep the load bearing capacity of the rotor blade under surveillance. By means of an operational modal analysis, OMA, natural frequencies, mode shapes and damping are measured [4][5]. Due to manufacturing reasons every rotor blade is an individual. Therefore, it is necessary to determine an own reference state of each rotor blade within the first time of operation. The modal parameters of a blade are changing with temperature, wind speed, pitch angle, etc. Additionally, there are different sources of blade excitation, e. g. by wind, gusts, tower blade passage, etc. which have to be considered in the context of OMA. In order to compensate these influences on the OMA results pattern recognition techniques are necessary. Therefore, all important combinations of the above-mentioned parameters are modelled together with the changes of extracted dynamical properties (features) of the blade. This correlation model between dynamics and environmental and operational conditions (EOC) built during the healthy state of the blade represents the reference state of this structural component [6].

During the whole life time of the blade the extracted features are compared to the reference model. Differences between the features and their model are evaluated in a statistical way. If the differences are significant from statistical point of view, blade damage can be assumed. Without using pattern recognition techniques for EOC compensation no damage detection is possible, also effects of the large damages will be masked by effects of EOC-changes on the extracted features, see [6] and [8].

The extraction of the dynamical properties itself is based mainly on the automatical pole extraction from stability diagrams obtained from the Stochastic Subspace Identification Method. Figure 5 shows the stable poles extracted from a rotor blade.

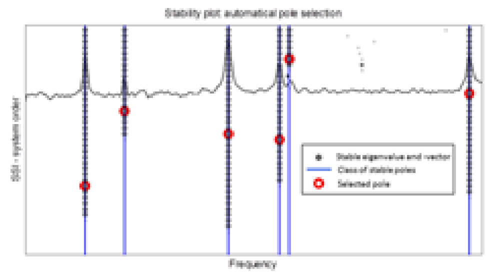

Figure 5. Stability diagram with automated pole selection.

Writing the eigenvalues over a longer time of operation it can be seen that the stable eigenvalues are varying due to environmental and operational conditions [9], so that - as mentioned before - these influences have to be compensated by means of pattern recognition techniques.

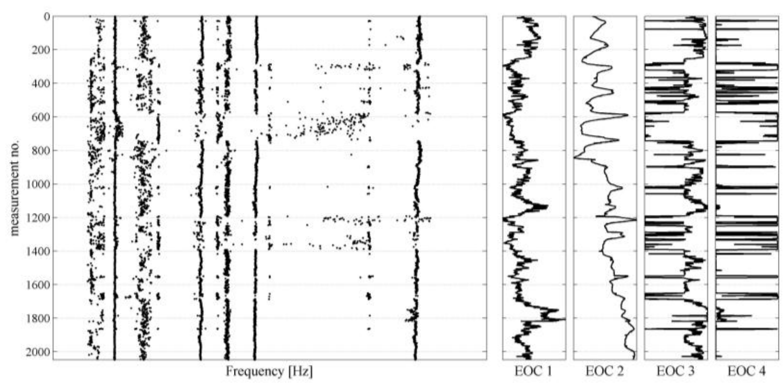

Figure 6. Long-term measurement and feature extraction of a rotating turbine.

High Point of multivariate SHM-System: The Damage Indicator

The multivariate SHM-system with 3 different measuring techniques acoustic emission (AE), acousto ultrasonics (AU) and operational modal analysis (OMA) in combination with a sensor network is able to detect a broad variety of different developing defects and damages. Rytter [7] established criteria for an assessment of structures related to their load bearing capacity respective to their extent of damage. The categories are:

- 1st level: detection of damage;
- 2nd level: localisation of damage;
- 3rd level: measure of damages;
- 4th level: lifetime prediction.

At the first level the system identification answers the question “Is damage or changing of environmental and operational conditions the reason for changing parameters? The second level localises the damage. On level 3 extension and character of damage are measured. The lifetime prediction is due to level 4. However, precondition is a lifetime model of laminated structures which does not yet exist. The matrix of table 1 is an advancement of RYTTER‘s classification which is transferred and adapted to the SHM Wind system [7].

As shown in this paper to detect all changes and damages mentioned in Table 1 it is necessary to process the measured data. The most important task is to reduce data to its representing features, which are sensitive to structural damage! Therefore, only changes of a structure in comparison with a reference state should be considered. Furthermore, an interpretation of the data with regard to structural behaviour is of great importance.

Table 1. Detection capability of SHM Wind for rotor blades.

	Acoustic Emission, AE	**Acousto Ultrasonics, AU**	**Operational Modal Analysis, OMA**
Detection of damage	**X**	**X**	**X**
Mode	integral	discrete	integral
Type of damage	Small, single damages at the whole blade, e.g. bursts of fibres, cracks of bonding, hits of hail	Small and big damages at the transfer path between emitter and receiver of guided waves (cracks, delamination, damages of the surface)	All bigger modifications of stiffness, mass and damping in the whole blade
Localisation of damage	**X**	x	
Extent of damage	**X**	x	All damages > threshold, defined by probability of detection, POD
Influence to stability of the blade			**X**
Warnings	Damage indicator with hierarchic decision support		

Allocation of tasks of different measurement in SHM Wind:
X: main task x: additional task

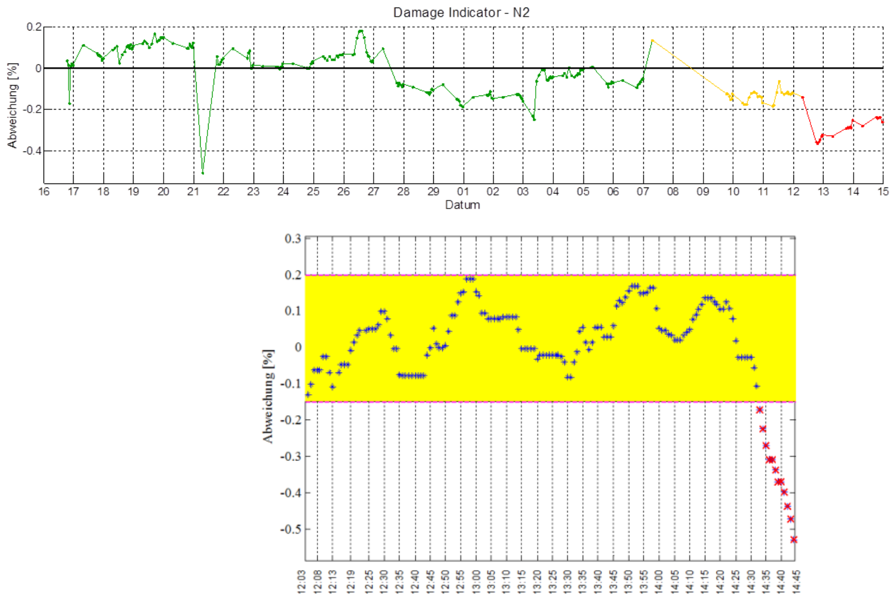

Figure 7. a, b: Objective of data processing is a clear indication of starting damage processes to allow for a stop right before failure.

Figure 7 represents results of OMA after EOC compensation. The change of the colour from green to red signals the proceeding degradation of the blade (7 a, top). Due to structural degradation repair measures should be started (7 b, bottom).

Instrumentation Plan of a floating Wind Turbine

As mentioned above, for floating wind turbines SHM is a must. In a European R&D-project HiPRwind the SHM-system for rotor blades will be further developed and expanded to the whole structure including floater, tower, blades and nacelle.

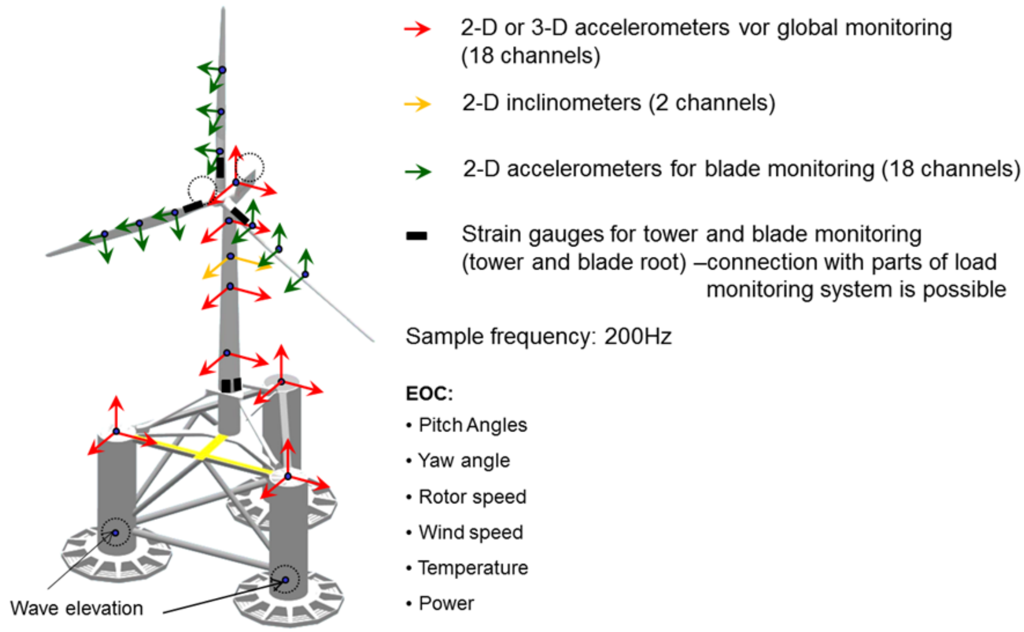

Figure 8. Instrumentation plan of HiPRwind floater.

This sensor grid fulfils two tasks:

- Delivery of measurement data describing the dynamic behaviour of a floating wind turbine. This measurement is important to verify load assumptions and simulation results.
- Development platform for an integrated SHM system for floating structures.

The challenge of this project HiPRwind is among others is the very harsh offshore environment and the interpretation of the dynamic behaviour of the complex structure.

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