Offshore Structural Health Monitoring: Concept of a Global Monitoring System Based on the Structure Dynamic Behaviour

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1. Abstract

To achieve the goal of making offshore wind energy much more affordable and competitive with other energy sources, wind turbine structures are continuously getting bigger and taller for higher power production. But considering that the civil engineering structures used in offshore wind industry are ‘relatively new’, it is important to minimize the risks resulting from the ever increasing upper limit. Although oil and gas industry has been operating offshore for many decades, it is not possible to directly use their experiences in offshore wind energy industry. This is because of the difference in structure types and the complex dynamics involved in an operating wind turbine.

Therefore, to make up for the lack of experience and to decrease the uncertainty involved in these ‘relatively new’ structures, it is important to implement a cost effective structural health monitoring system for offshore wind turbines and transformer stations. The monitoring system needs to be able to provide a real time performance of the structure being monitored. Most of the monitoring schemes for offshore structures implemented in the past are ‘local’ monitoring systems, which focus only on hotspots. But airwerk GmbH follows the concept of a ‘global’ monitoring system based on ambient vibration monitoring techniques, which focuses on global dynamic characteristics of the structure. The global monitoring approach has already been successfully implemented in five offshore wind farm projects. This paper will discuss the advantages of the global monitoring concept compared to local, its implementation and contribution towards making offshore wind energy not only favourable from environment point of view, but also a reliable and affordable energy source compared to other sources.

Keywords: SHM, global monitoring, offshore wind energy, structural dynamic behaviour

1. Introduction

Among the various methods of Structural Health Monitoring (SHM), vibration based SHM of civil engineering structures and infrastructures has been in practice for many decades. The main purpose of SHM is early detection of damage and significant deterioration of the structure being monitored. This will then enable for an action to be taken in good time, minimizing the maintenance costs and down time of the system. SHM data is able to provide the performance information of the system during operation, having reliable information reduces uncertainty and this in turn reduces the risk. This is in agreement with the ISO 31000 standard [1] definition of risk as, the effect of uncertainty on achieving objectives. In other words, the objectives of the system for which it is designed should not be interrupted or the interruptions should be kept to a minimum possible. The structural performance information of a system can also be obtained through conventional structural inspection methodologies, but assessing the status of structural components underwater is a challenge which cannot be simply done by standard methods. Also the unpredictable and sometimes very dangerous offshore conditions make the conventional methods impossible to implement. Therefore vibration based SHM comes in to the equation, which is implemented by installing an array of sensors to measure the vibration response of the structure, from which damage or structural changes of the structure can be detected.

In the case of offshore wind turbines, the objective is that they should operate continuously as long as there is enough wind. But this objective might not always be achieved due to failure of a major component(s) from the many electrical, mechanical or structural components in a wind turbine. This paper deals with the structural components (support structures), which includes the tower, transition piece and foundation structures.

2. Monitoring technique - Global monitoring system

Always, when developing a monitoring concept for a new system, it is important to tailor the already existing strategy and knowledge, so as to effectively serve the particular purpose at hand. In the case of offshore wind turbines, it becomes important to note that the structures are designed with higher partial safety factors and the structural components are subject to extensive quality controls during manufacturing. This is done to overcome the uncertainty resulting from the lack of experience in this industry. Therefore, it can safely be assumed that these structures are robust in nature.

For such a structure following the local monitoring concept in which sensors are placed all over the structure is not cost effective for the implementation of the monitoring scheme, as well as for data management and processing. Also installing sensors under water is generally not feasible. Therefore, the global monitoring concept which focuses on the monitoring of the global key structure performance parameters is more preferable for offshore wind turbines. In this approach only few, sensitive, reliable and strategically positioned sensors are used to catch the vibration characteristics of the structure being monitored.

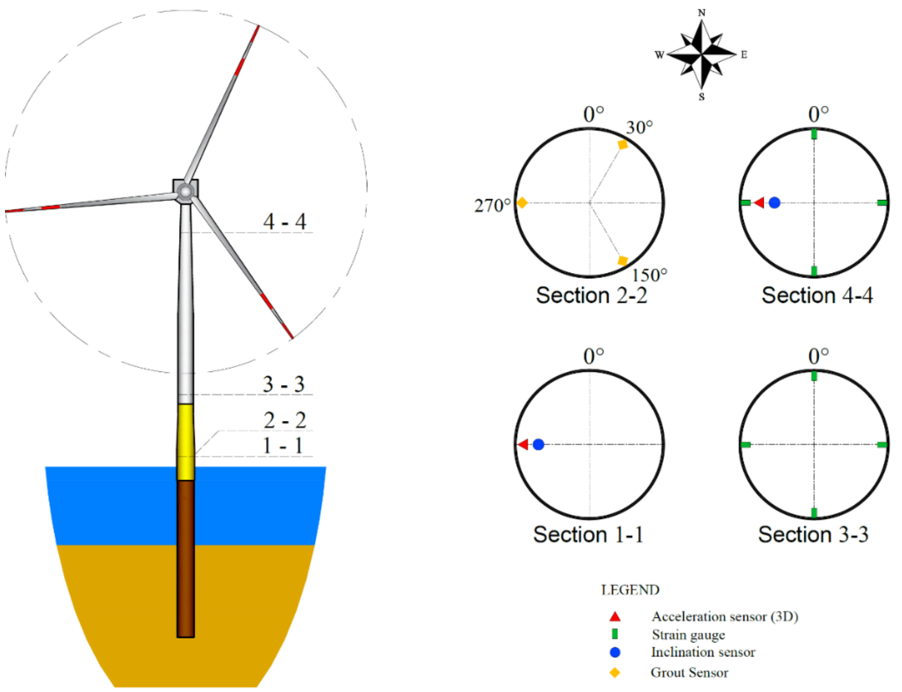


Figure 1: Typical vibration sensor positions for a global monitoring scheme

This approach becomes handy, especially for detection of structural changes for structures immersed in sea water, where it is not possible to place underwater sensors. All the sensors are installed above water (Fig. 1), where it is easier for access and maintenance works. But the sensors are placed so as to trace the changes in global characteristics of the structure, it is possible to detect changes in boundary condition or deterioration of the underwater structures from the due to its effect on the global characteristics. The most common sensors used are accelerometers, inclinometers and strain gauges.

3. Data evaluation technique

In permanent health monitoring schemes, huge amount of data is continuously collected, stored and processed. It is impossible to rely on manual data evaluation procedures and continuous detailed data analysis. Therefore, data analysis is semi-automated and divided in to different stages in which each step will initiate the next more detailed stage after a personal interference. airwerk GmbH follows a three stage data evaluation strategy:

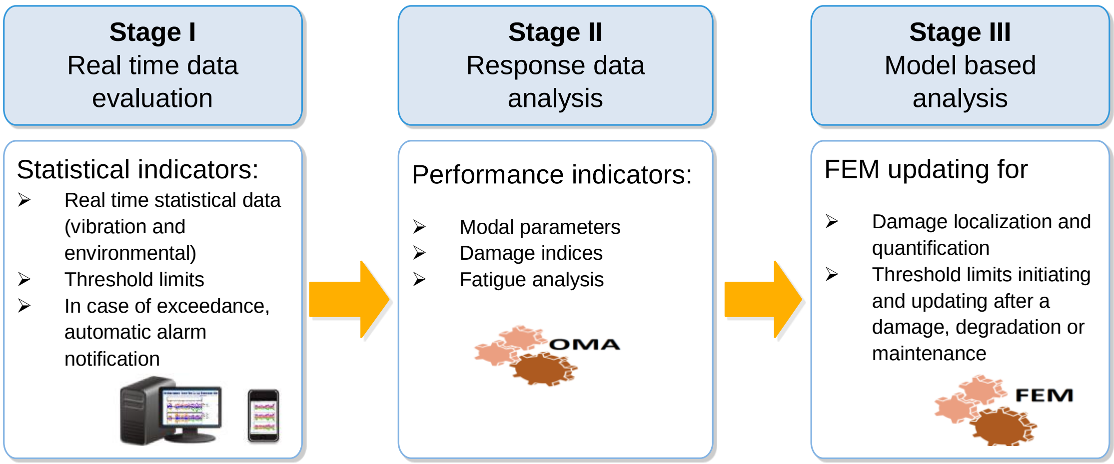
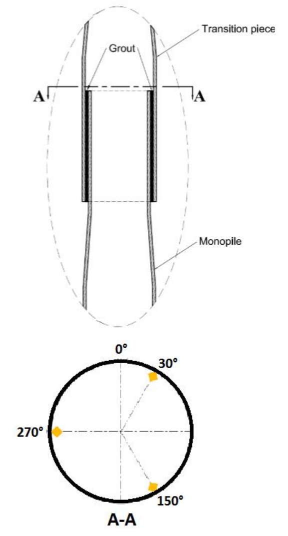


Figure 2: Three stage data evaluation strategy for continuous SHM data

3.1. Real time data evaluation (stage I):

Here 10 minute statistical mean, maximum, minimum and standard deviation of the real time monitoring data is continuously evaluated against predetermined threshold levels. This is convenient for the web based real time history data visualization. To effectively utilize the opportunity of having similar structures with similarly placed array of sensors, the correlation of signals from sensors on different structures at similar position is also a good first indicator to see if something is wrong at one of them. Also different sensors on the same structure are correlated for monitoring of sensor faults and backfilling of data from sensor failures. For automation of the process, threshold limits are predetermined for all channels, enabling implementation of an automatic notification procedure possible. For this purpose, environmental and operational conditions are investigated and compensated from a continuous minimum first one year monitoring data of the healthy structure. This is a very important step, as the structural response highly depends on corresponding operational and environmental conditions of the structure. Knowing this, it becomes possible to differentiate the responses due to structural changes from those due to changes in operational and environmental conditions.

In the case of wind turbines, due to their robustness, no deterioration or change in structure behaviour is expected during the first year of service. Once the thresholds are defined, automatic alarm notifications are implemented and the responsible operator gets an email or SMS notification whenever an alarm level is exceeded. If it is a serious one, stage two detailed data analysis is initiated for further investigation. It is obvious that, with ageing of the structure the threshold limits need to be updated, the same like the healthy state reference heartbeats of an old person, an adult and a child are not the same. This threshold limit updating is taken care of by stage three model based data analysis and previous monitoring data.



Grout sensor data
Sampling rate: 50 Hz, Duration: 24 hours
Alarm level 1 = ± 3.0mm, Alarm level 2 = ± 6.0mm
Maximum record for this day = - 0.62mm

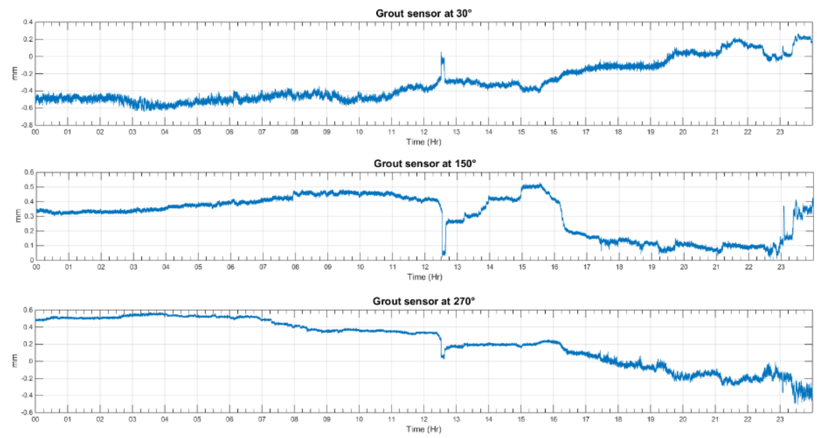


Figure 3: Stage I data visualization and alarm levels for continuous SHM

3.2. Response data analysis (stage II):

In this stage detailed analysis of the collected data is performed periodically or on demand to compute the key global parameters, which are sensitive to damage or structural deterioration. Then they are compared with the already determined healthy state reference parameters. The main parameters are structural modal parameters (natural frequencies, mode shapes and damping ratios). For this stage too, the healthy state reference parameters need to be predetermined. For such purpose stage III data analysis is employed. The deviation of the parameters from the reference values are traced in time domain to allow for damage and deterioration detection, as well as recalibration of the thresholds. System Identification (SI) technique called Operational Modal Analysis (OMA) is used for computing modal parameters. Unlike the classical experimental modal analysis, OMA needs as an input only the response of the structure to perform system identification. This tool is an ideal choice for large scale civil structures, where it is not possible to accurately measure or control the input loads and the effect of boundary conditions.

But when OMA is applied to an operating wind turbine, one of its basic assumptions that the test structure should not change in time is violated. This violation results from the time varying behaviour of an operating wind turbine due to the blade rotation, nacelle yawing and pitching of the blades. Therefore, the traditional OMA can only be used for SI of a standstill (parked) wind turbine but cannot directly be applied for an operating wind turbine. To overcome this limitation, several state of the art non-stationary system identification techniques have been developed. These techniques are capable of tracing the time varying dynamic behaviour of an operating wind turbine (Fig. 4).

Generally the output only system identification methods are classified in two major branches as stationary and non-stationary techniques (Fig. 4). The stationary case is commonly applied for system identification of large civil structures, which are time invariant and linear. The modal parameters are extracted from the response data in time or frequency domain. The frequency domain approach is based on Singular Value Decomposition (SVD) of the spectral density and is commonly known as Frequency Domain Decomposition (FDD) or its modified version Enhanced FDD, which can also estimate corresponding damping ratios. The technique EFDD is computationally faster and easier to understand compared to the time domain approach. But due to the conversion of the time history data from time domain to frequency domain by using Fourier transform, leakage is introduced as a result of periodicity assumption. The time domain approach, commonly known as Sub-Space Identification (SSI), is based on stochastic state-space models to estimate the modal parameters directly in time domain. In this approach the continuous time domain response data is first discretised using the Block Hankel matrix. Then, the lower half matrix (future) is projected to the upper half matrix (past) to create the covariance of the data at different time lags. And then, Spectral Value Decomposition (SVD) is performed on the resulting matrix to obtain the observability matrix from which the modal parameters are estimated by Eigen value decomposition of the system matrices [2].

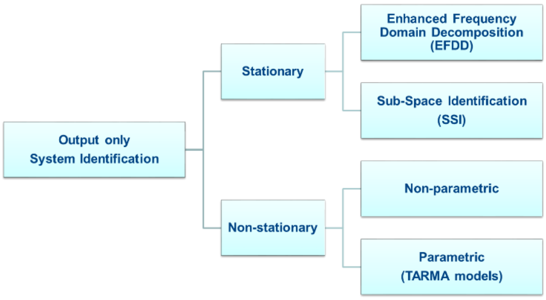


Figure 4: Trends of output only system identifications techniques

The second major category is the non-stationary system identification method, which is applied to time variant structures with non-stationary random vibration responses and/ or non-linear dynamics [3]. They are further classified in to non-parametric and parametric methods. The non-parametric methods are generally based on the representation of the vibration energy simultaneously as a function of frequency and time. They make use of the Short-Time Fourier Transform (STFT) spectrograms. While the parametric methods are based on Time dependent Auto-Regressive Moving Average (TARMA) models. The parametric models are more preferred to the non-parametric due to their improved tracking of the time varying dynamics, better accuracy, higher resolution, better flexibility in analysis and control [3]. Therefore, the time varying dynamic behaviour of the operating wind turbine is traced with higher accuracy in time domain for all operational and environmental conditions, so as to be able to clearly distinguish the changes in dynamic behaviour as a result of damage from those caused as a result of the operation and environment condition.

In stage two data analysis, other parameters are also evaluated, such as the vibration intensity and energy dissipation [4], which are also very useful parameters capable of detecting structural changes in its early stage. Also if strain gauges (rosette type) are implemented in the monitoring scheme, then it is possible to compute the principal and shear stresses along with their orientations using the strain time history data. Furthermore, fatigue analysis can be done using the rain flow counting method to estimate the remaining service life time of the structure. Also to justify if the system has not yet consumed its fatigue life and can operate beyond its design service life time with minimum risk.

3.3. Model based analysis (Stage III):

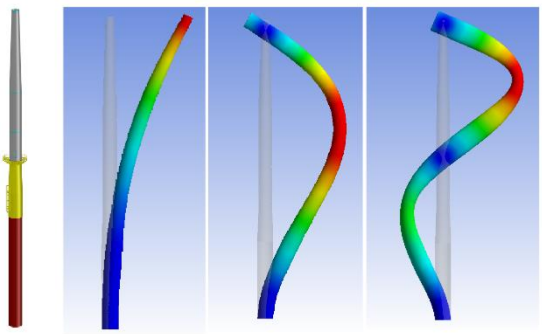


Figure 5: Stage III, FE model based analysis

The third stage data analysis is based on Finite Element Model of the structure. The FE model is first validated from the measured dynamic parameters of the as built healthy structure, so that it fairly represents the as built physical structure. Then to make up for the lack of damage scenario experiences, the possibly expected damage scenarios are simulated on this model and the damage sensitive parameters are traced with increasing damage levels as well as superposition of scenarios. The results are to be used for defining the threshold limits of the parameters for stage II data analysis. Also the rate of deviation of these parameters is to be later used for damage quantification and localization. The FEM model is continuously updated for the changing parameters due to damage, deterioration, maintenances and any other changes during the service life of the structure which affect the structural dynamic behaviour. With this information it is then possible to keep the thresholds limits up-to-date.

4. Application for life cycle management

To effectively utilize the SHM data processing results, it is very important to integrate them to asset management. Therefore, the continuously collected huge amount of data needs proper management for safe retrieval, storage and analysis routines. The summary of all the processes involved can be referred to in figure 6 below. The SHManager^{TM} [5] web user interface developed by VCE and airwerk GmbH is designed to provide the end result of the continuously collected huge amount of data, so that it provides real time support for decision making concerning inspection and maintenance scheduling of the wind turbine for life cycle management. The client has a login secured web access for visualizing real time history data of all channels, alarm notification, data downloading, customization of channels to view and automatic generation of periodic or on demand reports. Further information may be obtained at www.shmanager.org.

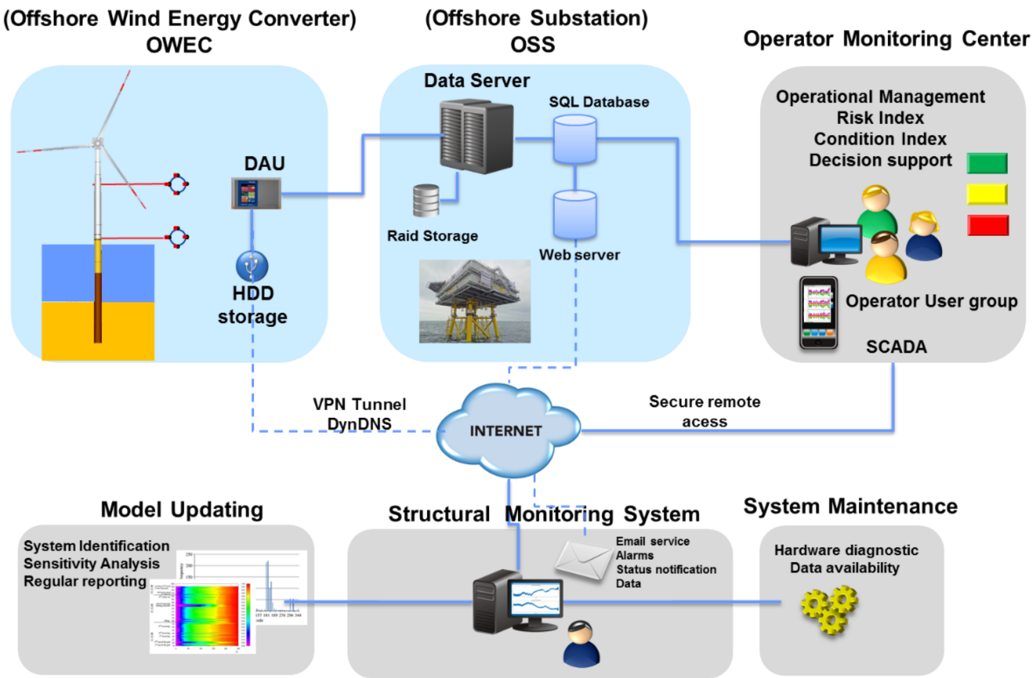


Figure 6: Overview of the data management process

This is implemented in line with the approach for risk estimation defined by the European Collaborative Research Project IRIS [6, 7]. Risk is the central focus point of the approach, with its definition as the probability of occurrence of unacceptable performance or the probability of failure of a component when a single parameter (or a group of parameters) exceed their predetermined threshold levels. The performance of the offshore wind turbine support structure is evaluated by comparison of the measured parameters to the already predetermined healthy state reference parameters. The further the deviation the more the risk. But this risk needs to be quantified in terms of the resulting damages for the structure, environment and financial losses.

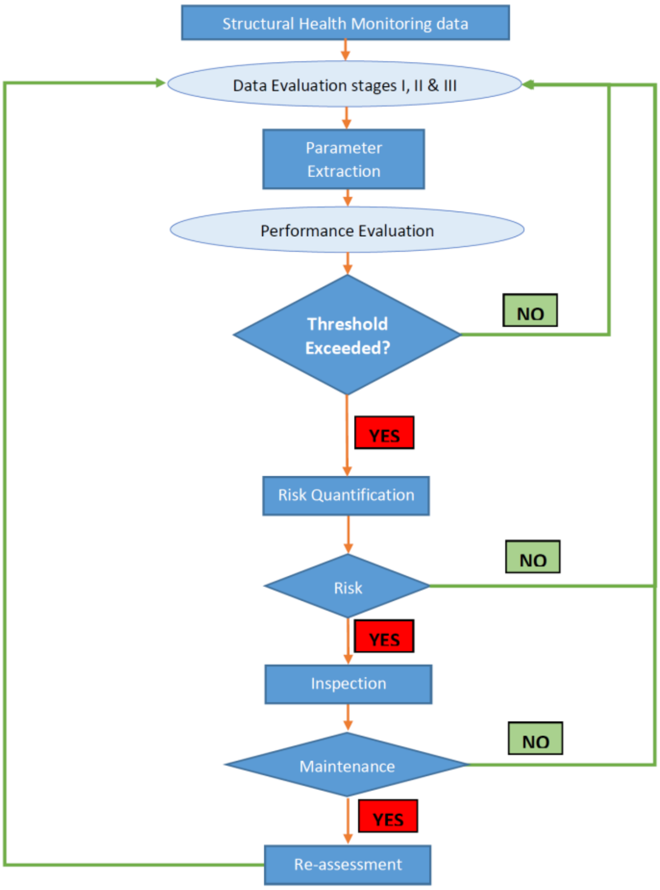


Figure 7: *IRIS Risk Assessment Tool implementation for SHM data*

5. Conclusion

The integration of the results obtained from the structural health monitoring data evaluation to asset management can significantly decrease the life cycle cost of the wind turbines and contributes towards making wind energy not only a clean energy source but also a reliable and affordable source competent with the other energy sources.

6. References

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