STRUCTURAL MONITORING SYSTEM FOR OFFSHORE WIND TURBINE FOUNDATION STRUCTURES

J. Wernicke, S. Kuhnt, R. Byars (WindForce GmbH)

Paper presented at the European Wind Energy Conference & Exhibition,
28 February – 2 March
Athens, GR

Keywords:
LOADS; FIBRE OPTIC SENSOR; RESIDUAL LIFETIME ESTIMATION; OFFSHORE WIND; RELIABILITY

1 Summary

Fibre optical sensors (FOS) are useful for a variety of turbine control and protection functions. Online load measurements of offshore wind turbine foundations throughout the turbine lifetime allow structural load monitoring and residual life time estimation. Based on the data the overall system performance can be optimised, and in the event of failure the data can be used for a meaningful root cause analysis.

Event based maintenance and repair can be scheduled dependent on real time load information for individual turbines, which has the potential to lower operational cost and improve reliability. Data analysis regarding frequency shifts, crack initiation, vibration or overload conditions enables proper action to reduce cost and component failure.

WAVEMON™ is a product family based on data acquisition using fibre optic Bragg gratings (FBGs) for structural monitoring of offshore wind turbine foundation structures. The data collected over the lifetime of the offshore wind turbine generator will be evaluated periodically and provide input for the project management. Main goals of the product are the reduction of operational costs and improvement of the reliability of offshore wind turbines. The first hand knowledge of the actual load history of each wind turbine allows optimisation of maintenance costs and reliability over the service lifetime.

Jens Thomas Wernicke
jens.wernicke@wind-force.com
Phone: +49-471-902628-61
Fax: +49-471-902628-69

2 Introduction

Offshore wind turbine generators require innovative solutions to lower operation and maintenance costs in order to achieve a competitive energy price.

The typically high capital costs and extreme environmental conditions of offshore wind turbine installations define the need for an innovative monitoring system for these projects. Increasing understanding within the industry of the real loads due to wind, current and waves is very important, and correlation between reality and simulation provide a tool for an effective project management, as well as input to next generation designs.

3 Load Measurement in Foundation Systems

The measurement of strain in offshore wind turbine foundation systems under water is difficult to realize with conventional strain gauges. The technology of fibre optical sensors based on fibre Bragg gratings (FBGs), which are commonly used in fibre optic communication systems, shows a number of technical advantages.

WAVEMON™ Foundation Monitoring System works with input data from FBGs. Unlike most fibre optical sensors, this system employs a “cold written” FBG, which allows the fibre to retain its structural integrity, remaining robust for handling and installation. The following main features of fibre optical sensors recommend its application in wind turbines foundations.

- Small cross section, low weight, very low heat conduction
- Long signal transmission lines, with very low or negligible losses
- Long term stability under operation in hostile environments (EMI, weather, chemicals, high/low temperatures)
- Remote, electrically passive sensors, ideal galvanic separation
- Multiple sensors (up to 100) linked on a single conductor with only one mechanical connection point, low cabling.

3.1 Structure of the Fibre Optical Sensor

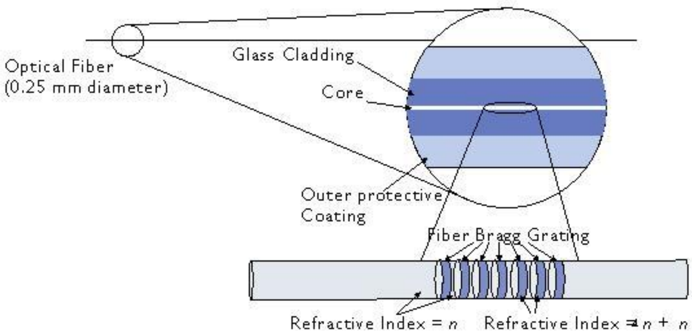

Figure 1: Structure of the fibre optical sensor

The optical fibre has a diameter of 0.25 mm which includes the core, the glass cladding and the coating. The FBG sensor consists of a small periodic variation in the refractive index of the optical fibre core. The periodic variation is made by a high powered ultraviolet laser. By irradiating the core material of photo sensitive quartz glass locally with UV-light, the refractive index is increased at certain locations along the fibre. These locations are spaced in equal distances, the entire sensor having a length of about 3 – 14 mm. [1]

3.2 Structure of the Measurement System

The main components are:

1. Interrogation Unit (IU) as source and receiver of light, data processor, communication interface, transformer, software
2. Interconnecting Fibre (IF) for data transfer between IU and sensor arrays
3. Sensor Arrays
4. Temperature compensation sensor
5. Support brackets (customised according to design requirements)

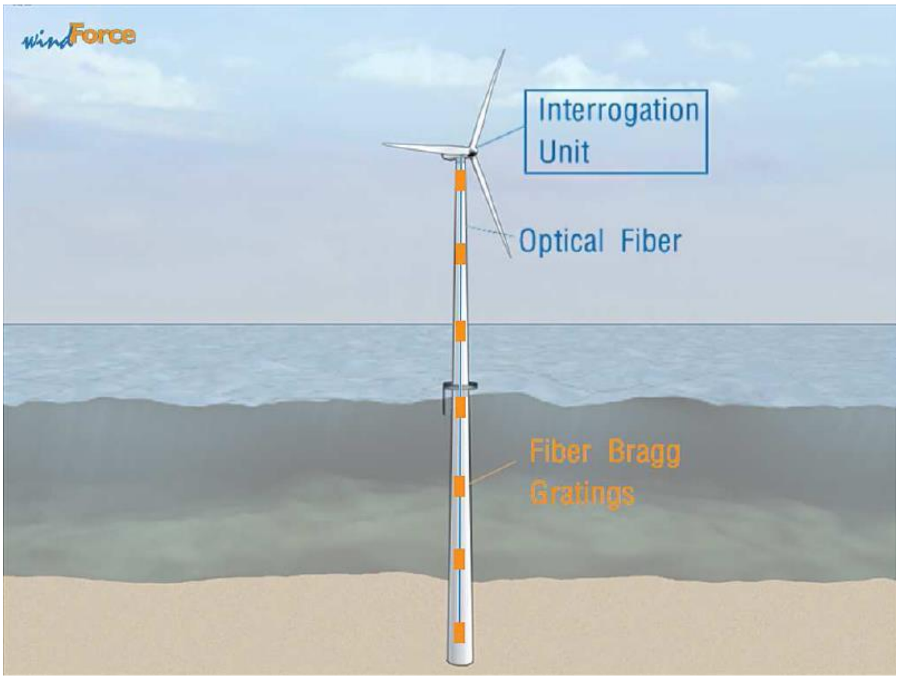

Figure 2: Structure of the Measurement System in a wind turbine foundation system

3.3 Function of the Fibre Optical Sensor

A light source provides a broadband input signal in the fibre. When passing an FBG, the light is reflected within the pre-selected narrow wavelength band around λ_B. When the sensor is exposed to a strain, the distances of the grating change, which also changes the wavelength of the reflected light. The analysis of the characteristic of the reflected light is used to measure the strain at the sensor location. Shifts in the reflected wavelength are proportional to change in elongation caused by temperature, or load induced strain which can be computed to stress based on the component geometry. [2]

Because the optical strain sensor is sensitive to temperature changes, the strain measurements must be temperature compensated.

One of the main advantages of the fibre optic sensor is the multiplexing feature using one single fibre with multiple FBGs without interference between the single measurement points. This system is based on time division multiplexing, which allows the interrogation unit to distinguish between individual strain sensors by using their physical position in the array as a reference. By measuring the time taken for the light to travel from the interrogation unit to the sensor and back, it is possible to calculate its physical distance from the interrogation unit, and therefore which sensor the signal originated at. [3]

4 WAVEMON™ Application

Structural monitoring is indispensable for a reliable operation of an offshore wind park. Operational costs have the potential to be reduced by the analysis of foundation load history of individual offshore wind turbines throughout life time. This data can be used to schedule maintenance and service activities based on extreme events or accumulated fatigue ("event-based maintenance"). Criteria for data acquisition are:

- Measurement of height, direction, and frequency of waves
- Measurement of wind- and tide currents
- Traceability of single events (extreme loads, collisions, etc.)
- Traceability of fatigue loads for residual lifetime estimation
- Monitoring of design parameters
- Input to turbine control for loads reduction capability
- Early damage detection
- Demonstration of insurability of foundation structures

WAVEMON™ provides an array of solutions with a focus on improvements in performance, reliability and availability of the wind turbine, some of which are described below:

Structural Monitoring

Condition monitoring of the monopile and its support conditions. Single events can be documented and the relevance towards failure can be estimated.

Active Control

Damping of compound loads.

Preventive Maintenance

Service activities based on event logging and data evaluation.

Residual Lifetime Estimation

Comparison of individual load history during operation with design load simulations.

5 WAVEMON™ Test Structure

The first test installation was performed on the monopile of the wind met mast "Amrumbank West". A total of four arrays were installed, with sensor locations above and below the water line as well as below the mud line. The sensor arrays are spaced at 90 degree intervals around the interior of the 3 meter diameter steel monopile in order to gather redundant bi-directional loads data. This installation was done in parallel with a strain gage measurement system installed by a third party.

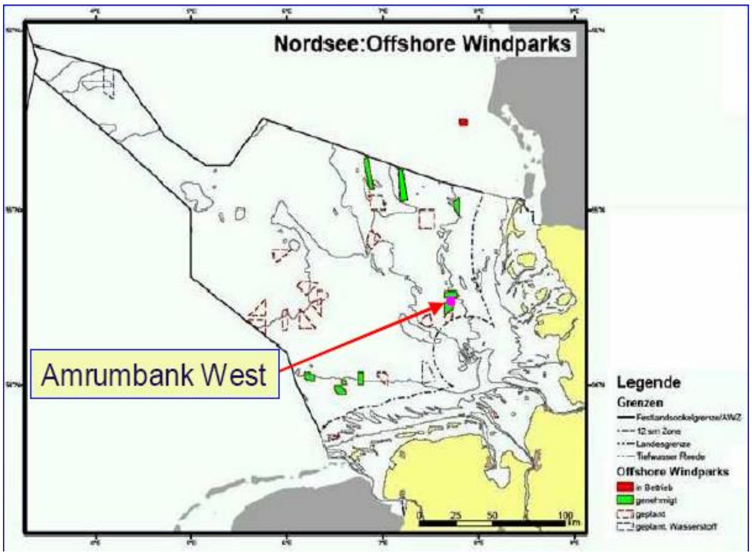

Figure 3: Location of the met mast "Amrumbank West"

Figure 4:The met mast mounted on the completed monopile

The interrogation unit is located in a service room at the top of the monopile, above the water line. It is comprised of an integrated single board computer and in this application communicated over a CANBus system with a third party data collection system.

The arrays were bonded to the structure on land prior to transporting and driving the monopile into the sea floor. The interrogation unit was also installed in the top section of the monopile on land. Final connection of the sensor arrays to the interrogation unit and commissioning of the system was performed after installation, at the offshore location.

The surface was prepared by grinding and cleaning the steel. The raw fibre was then laid onto the surface and covered with a protective layer of fibreglass and epoxy. Each sensor location was precisely bonded to the steel surface and covered separately. This installation technique allowed a continuous run of the fibre from the top to the bottom of the monopile with no connectors or transition areas around the sensors which represent potential breakage points. This technique also resulted in a significant time savings over the strain gage installation, as well as a much smaller system profile associated with the same number of sensor locations.

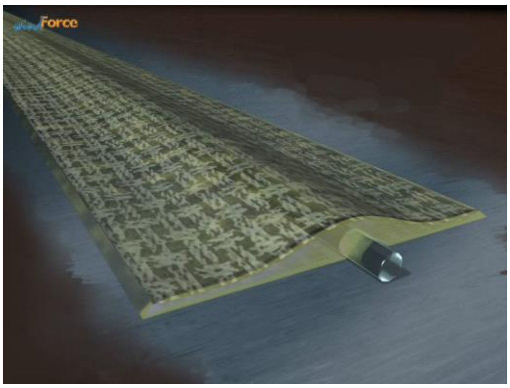

Figure 5: Fibre Optic Sensor bonded to steel surface and covered with protective tape and epoxy

Slightly different procedures and materials were used for each of the four arrays for evaluation purposes. An upcoming installation will use the best of the materials and techniques from the first installation and will verify cost and time savings over strain gage installation requirements.

6 Test Results

6.1 Sensor signals during operation

Figure 6 shows one sensor signal during a ten minute data collection period. Figure 7 shows a frequency analysis of the ten minute data file, with an expected peak at the natural frequency of the mast.

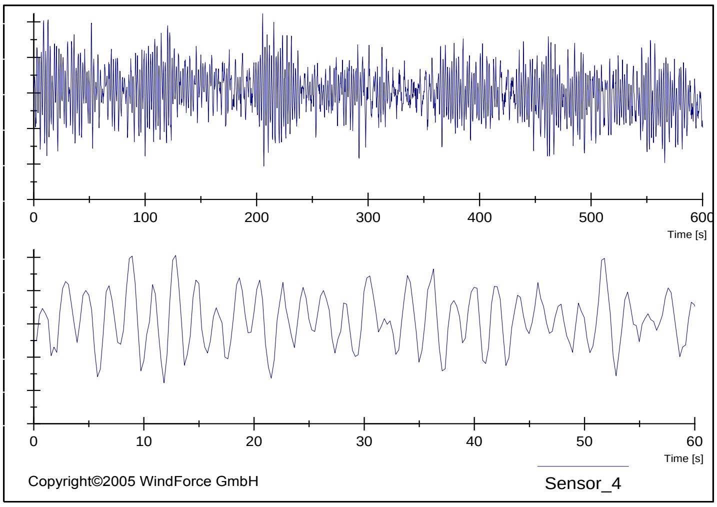

Figure 6: Real time load history ten minute file

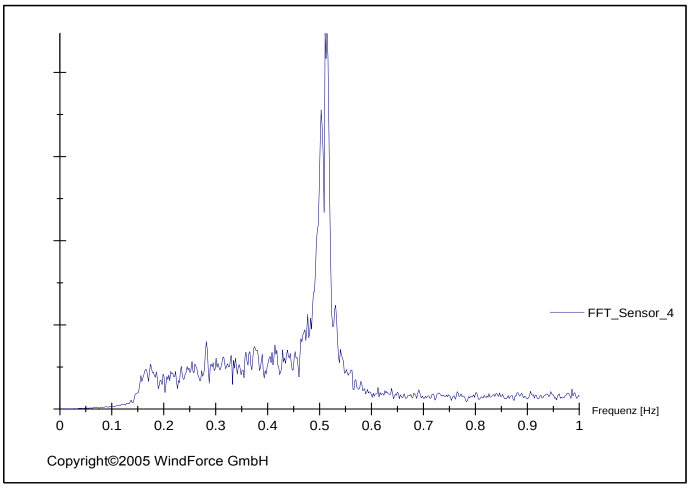

Figure 7: Frequency analysis from load history ten minute file

7 Ongoing Development Efforts

Current and upcoming lab and field installations continue to improve the installation techniques and materials, which is key to maintaining the robust nature of the system while minimizing investment. The next phase of the testing will focus on correlating real world data to design simulations. This work will serve to assess expected performance of the structure in real world conditions and to improve simulations for future installations.

8 Conclusions

The test installation proves the data reliability from the WAVEMON™ system. This supports the goal of using the data as input to algorithms for advanced functions such as residual lifetime estimation, event based maintenance, structural monitoring, and active control.

Furthermore the test installation was used to standardize the installation technique to a serial product level, which proved to be a significant savings in time, cost, and space required compared to a strain gage based measurement system with the same number of sensor locations. The upcoming installation will use the best of the techniques and materials developed in this phase.

Further data analysis will compare FOS measured loads to simulated loads.

9 References

1. *Fibre Bragg Gratings*, R. Kashyap, March 1999

2. *Fibre Bragg Gratings Fundamentals and Applications in telecommunications and sensing*, A. Othonos, K. Kalli, June 1999

3. *Novel resonant cavity TDM demodulation scheme for FBG sensing*, G.D. Lloyd and I. Bennion, L.A. Everall, K. Sugden