Innovative monitoring of the North Sea Foundations

In 2010 researchers of the acoustics & vibrations department of the Vrije Universiteit Brussel (VUB) started working on the topic of FSHM (Foundation Structural Health Monitoring), back when this abbreviation was not very well known in the wind power industry. Going back six years ago, the main research in the field of sensors and monitoring was targeted at the rotating equipment in a wind turbine, so called CMS (Condition Monitoring Systems) as it is known in many industries. Gearboxes and generators were the key components to be monitored to predict failures in order to reduce the expensive maintenance costs associated with these parts. PES finds out more.

Currently, wind turbine drivetrains and electrical components are no longer the only components that are equipped with sensors and monitoring tools: also structural parts as blades, towers and foundations are now being instrumented with dedicated sensor layouts to monitor their health and even predict their residual lifetime using smart data-analysis and interpretation of the loads they encounter during their operational life.

As part of OWI-Lab - the Belgian research, development and innovation platform for wind energy which was also set up in 2010 - specific research projects have been set up that aimed at reducing the levelized cost of energy (LCOE). In partnership with several operational offshore wind farms in the Belgian North Sea, specific research measurement campaigns were set up.

Structural Health Monitoring has been one of the key topics addressed within OWI-Lab together with VUB as research partner, thanks to their experience in this field for several years. Dr. Ir. Gert De Sitter, co-founder of 24SEA, elaborates: “In the past our research group applied its knowledge of SHM only in the field of civil structures and aerospace applications like bridge monitoring and airplane flight flutter testing. This knowledge was adapted and fitted for the use of structural monitoring of offshore structures, a process that took five years of testing, tuning and adapting the measurement set-ups, and more

specifically the software for smart data interpretation".

The outcome of the first research projects was beneficial for the operators for two reasons. Firstly, the operators gained insights in the operational status of the foundations in order to plan maintenance if needed. Secondly, the historical structural data could be used to optimize the designs of future foundations layouts using less steel, and so leading to reducing the LCOE.

In general, the broad motivation of developing solutions for foundation structural health monitoring was to provide the wind farm developers and operators those insights that are crucial to minimize construction and installation costs of future offshore structures and assess the lifetime of existing structures and reduce their operation, maintenance and inspection costs.

Since February 2016 the developed foundation monitoring systems and data analysis services are commercially offered by an OWI-lab spin-out company called 24SEA. 24SEA develops and installs the complete SHM system, provides detailed installation reports, manages the remote access, data transfer and data storage, analyzes the data and provides reporting.

The experience of the founders of 24SEA, and initiators behind the OWI-lab FSHM

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services, with advanced data analysis and structural health monitoring can historically be found in the fact that they obtained their PhD within the Acoustic and Vibration Research Group (AVRG) of the Vrije Universiteit Brussel. AVRG has over twenty years of experience with the development of advanced Experimental and Operational Modal Analysis (OMA) techniques, NDT techniques and structural health monitoring solutions for various applications.

Their offshore experience and track record in the domain of offshore wind started in 2011 with the Belwind offshore wind farm (a 165 MW farm). A full foundation monitoring system, including grout monitoring, dynamic monitoring and load monitoring was installed on one turbine in 2011 and has been operating ever since. In 2013 similar foundation monitoring systems were installed on two turbines in the Northwind offshore wind farm (a 216 MW farm).

In the summer of 2015 a full foundation monitoring system (accelerometers, inclinometers, strain gauges) was installed

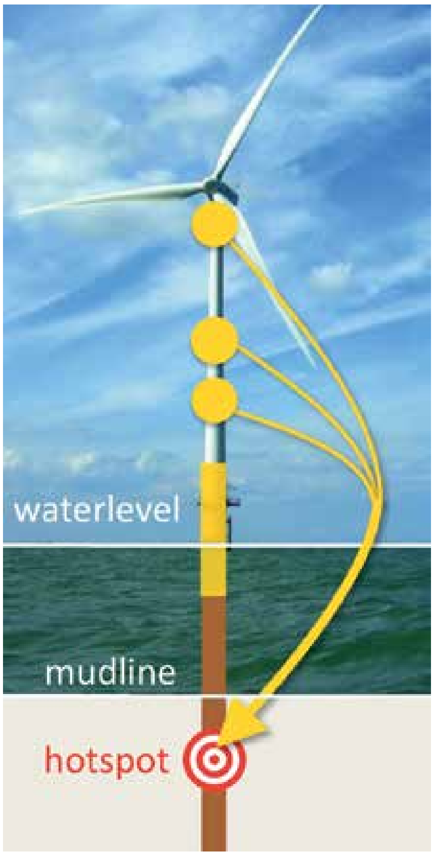
on two jacket foundations within the offshore wind farm C-power (Belgium). Recently 24SEA completed its most recent project of equipping three turbines with a full foundation and grout-monitoring system within the Prinses Amalia offshore wind farm (Netherlands). Today 24SEA is in the design phase for two new projects, respectively in Belgium and the UK, for the installation of a total of 9 turbine foundation monitoring systems.

Most foundations structural health monitoring solutions combine a broad spectrum of existing monitoring solutions and are equipped with a multi-physics sensor lay-out. Some standard monitoring solutions and corresponding sensors are:

- Grout Monitoring: this solution, based on displacement sensors, allows to continuously measure the relative displacement and the relative angle between the monopile and the transition piece for grout assessment.
- Dynamic Monitoring: this solution, based on accelerometers and inclinometers, allows to continuously monitor the vibration levels, inclinations, resonance frequencies, damping values and mode shapes of the offshore structure.
- Load Monitoring: this solution, based on strains gauges, allows to continuously monitor the interface loads, stresses & bending moments.

The offshore applications require robust and reliable hardware achieving high data availability and minimum interventions. The following hardware components are part of a typical FSHM system and they can either be installed during the fabrication phase onshore or offshore after completion of the offshore turbine:

- Sensors (including sensor housing and sensor mounts)



- Cables and connectors (including junction boxes, cable routing and fixations)
- Data Acquisition Unit
- Power supply unit (including electrical grounding, over voltage protection)
- Network components

The following hardware components are present onshore or in the offshore substation:

- Data storage and analysis servers

24SEA uses a modular approach (each enclosure contains a specific component), which results in a flexible set-up that can be easily extended or adapted. All modules have magnetic mountings for easy removal. An additional advantage of this modular approach with magnetic mountings is the offshore maintainability of the system.

Various suppliers provide data-acquisition systems that meet the general specifications. At present 24SEA uses the Compact Rio platform from National Instruments. This platform is very robust, has modules for all types of measurements and is easily scalable. 24SEA uses in-house developed software that measures continuously and sends data every 10 minutes to the onshore server. For every 10 minutes of data from each sensor, simple statistics are calculated. More advanced secondary parameters (e.g. resonance frequencies, damping values, relative displacements and inclination angles, bending moments) can be added in a second step. All data logging units are synchronised and all data receives a UTC time-stamp. This enables future data classification, correlations analyses and data normalization. Finally, all equipment can be maintained remotely and includes an alarming system, which can send e-mails, text messages and can be coupled to the SCADA system.

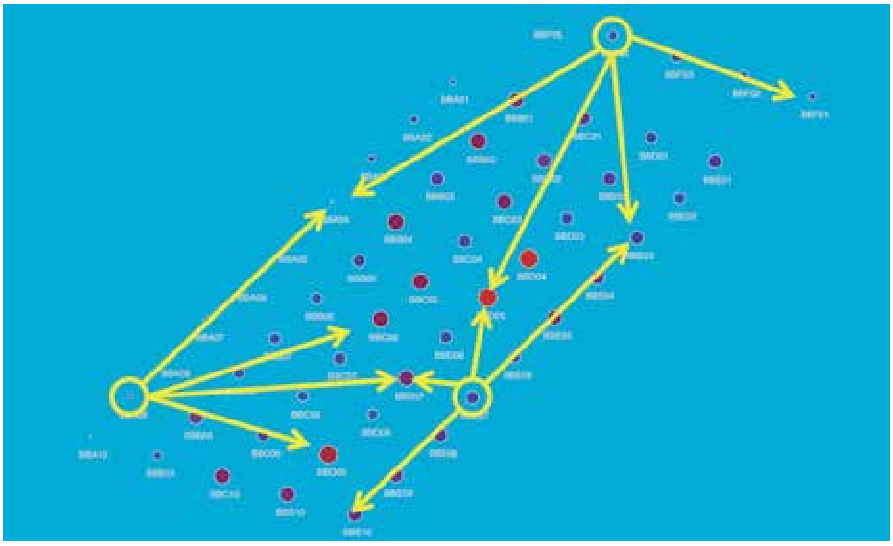
24SEA strives to continuously improve their data analysis techniques for enhancing the decision support of the operator. Its team members continue to innovate by participating in national and international research and joint industry projects.

Today's main research topic, which is currently investigated in cooperation with Parkwind and C-Power and the support of OWI-Lab (Vrije Universiteit Brussel) is dealing with the monitoring and prediction of the ageing process of offshore foundations. Most foundations for offshore wind are designed to withstand a given lifetime, typically 20 to 30 years, without the need for any inspection or maintenance. Nonetheless there are several reasons why operators want to keep track of their substructures. This implies that in future decisions about maintenance, lifetime extension or re-powering, the consumed fatigue life needs to be taken into consideration.

For offshore wind turbines on monopile foundations fatigue life is a design driver. During the design of these structures fatigue due to combined wind and wave loading is one of the most important problems to face. With ever growing turbine sizes and greater distances to shore the demand for load monitoring of those foundations has become more relevant than ever. In particular, the monopile foundation, which represented over 80% of the total installed offshore wind turbine capacity by the end 2015, has been pushed in terms of weight and diameter. Especially with the larger turbines the wave induced vibration becomes more important. Since a lower natural frequency means an increased interaction with the wave loads, this can lead to accelerated fatigue.

With uncertainties in earlier designs and consequent design conservatism there is however potential room for lifetime extension of these foundations. Load monitoring however does not only provide the operator with opportunities with respect to life-time extension. It can also provide the operator with decision support during the operation and maintenance phase e.g. the following questions can be answered:

- Can the number of periodic inspections be reduced?
- What should be done when a crack is detected during NDT inspections?
- Which long-term maintenance actions are required with respect to the coating or cathodic protection?



- What is the effect of developing scour or rotor-imbalances on the remaining useful lifetime of the structure?.

Fatigue assessment at hotspot locations can either be performed by directly analysing data from strain gauges installed near these locations. Therefore, standard rain flow counting algorithms can be applied in combination with Miner's law and appropriate SN curves to calculate the accumulated damage. Once the link between fatigue rates, SCADA and meteorological data is drawn it is possible to estimate the remaining useful life taking into account the expected environmental and operational conditions during the entire lifetime of the turbine.

However, many of the fatigue critical locations are at locations that are difficult to equip with sensors. In addition, since the number of sensors to be installed on the wind turbines need to be as low as possible, and also the number of instrumented turbines within a wind farm is limited, new data analysis approaches need to be developed.

Hybrid approaches can be implemented, where part of the signals are actually measured and the others are computed with numerical and data driven models. These can then be fed to the structural health monitoring algorithms as virtual channels and the complete response of the structure or fleet can then be computed.

In order to validate these innovative monitoring approaches Parkwind initiated in cooperation with Vrije Universiteit Brussel/OWI-lab a national research project with the support of the Flemisch Agency for innovation by Science and Technology (IWT). Two of the research topics that will be adressed within this project are:

- The virtual sensing technique
- The fleetleader concept

Virtual sensing utilizes a limited set of response data from more reliable accelerometers and strain sensors at easily accessible locations. This structural health monitoring approach has thus the ability to interrogate the entire structure and accurately assess fatigue life consumption and remaining useful life at all fatigue hot spots. Within this research project 3 monopile foundations have been equipped with optical fibre bragg strain gauges over the full length of the monopile. Amongst other research questions this set-up will allow to validate the virtual sensing by comparing the estimated strains with the measured strains below the seabed.

The fleetleader concept tries to answer the following question: What about the foundations that are not monitored? Typically only a few turbines to max 10% of the wind farm -- according to BSH requirements -- are equipped with a foundation monitoring system.

The fleetleader concept uses a limited number of turbines, called fleet leaders, instrumented to measure the load history of the substructure. The recorded load histories allow the definition of the consumed life time of the turbine and calculate the remaining useful life. To assess the condition of the entire farm, the results of the fleet leaders will be extrapolated to the other turbines using models trained on the fleet leaders.

These models will not only take into account the operational condition of each turbine but also its position within the wind farm, considering both the local wind and wave effects but also the local soil conditions and their effect on respectively the turbulence and dynamics of the investigated foundation. Recent work concluded that the fleetleader concept is a viable research goal but still requires continued research.

To conclude offshore foundation structural health monitoring is offering a lot of opportunities to lower the LCOE of both existing and future offshore wind farms. It combines state-of-the-art monitoring solutions coming from other industries, such as civil and aerospace, with innovative data-analysis tools, that allow to take into account the large operational and environmental variability, typical for these structures. It is also inspiring how all involved stakeholders, ranging from the designers to the contractors and operators can benefit from the knowledge build up, gained by measuring on the real structures within real offshore wind farms, in their daily activities. ■

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