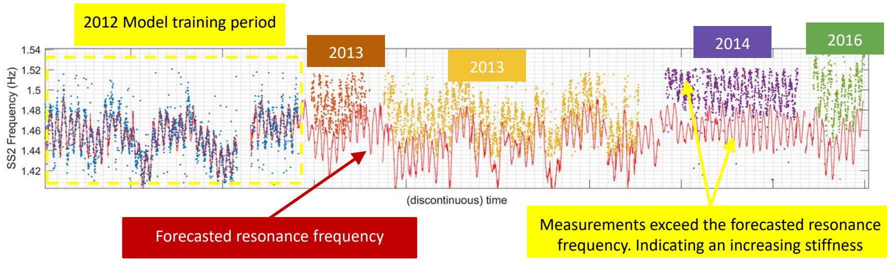
# Monitoring substructures – a long term experience

As of 2011 OWI-lab, in co-operation with the Vrije Universiteit, Brussels (VUB), has been conducting a long term structural monitoring campaign at all Belgian offshore wind farms. The measurements focus on the structural health of the substructure (SHM) rather than the wind turbine itself. PES is pleased to share this important research, which is sure to have an impact on future wind farm monitoring.

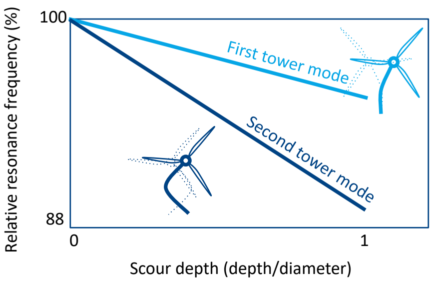
This different focus was motivated by the operators of offshore wind farms. While the correct operation of the wind turbine is typically covered under a service level agreement with the turbine OEM, other vital components such as the substructure, foundation and cables along with the offshore high voltage station and grid infrastructure, fall under the responsibility of the operator. It was from their concerns that OWI-lab started to research and develop tailored monitoring solutions and search for decision support tools towards the substructure.

### Dealing with operators' concerns

One particular concern posed by the operators is the development of scour around the foundation. During scouring the seabed around the foundation is eroded, reducing the embedded length




OWI-lab scour-monitoring strategy




Current monitoring strategy

of the foundation. This has a direct effect on the structural properties. With the development of a scour hole, the exposed length increases and the resonance frequencies of the structure will reduce. This reduction in resonance frequencies can lead to an increased dynamic amplification of the wave loads and consequently a decreased fatigue life.

The current monitoring strategy for scour is to perform regular bathymetric surveys near the substructures. Such a survey gives a snapshot in time of the condition of the seabed. However, with scour holes developing and disappearing in a matter of days this might give a false image of the actual condition.

Moreover, the size and depth of a scour hole itself do not provide any direct insight in to the effect it has on the substructure. As such a structural analysis has to be performed in a second phase using simulations to provide e.g. the changed resonance frequencies of the substructure.

OWI-lab decided to flip the scour-monitoring strategy around. Rather than to focus on the development of a scour hole, the structure itself is monitored. By installing accelerometers on the tower and substructure, at easily accessible locations, the resonance frequency of the foundation can be monitored over time.

In particular the second tower mode resonance frequency is interesting for this application, as it is more sensitive to the development of a scour hole. However, this frequency also varies with environmental conditions, such as the tidal level and a model was trained to compensate.

Interestingly, long term results at a site revealed an increase of the resonance frequency w.r.t model over time, hinting at an increasing stiffness of the soil.

This is exactly the opposite of scour development. The exact cause of this increasing stiffness is impossible to determine without further geotechnical or bathymetric surveys. But the most likely cause is the densification of the sandy soil at the investigated site.

The current monitoring effort also serves a second purpose as a design verification tool, to quantify the difference between as-designed and as-built. In this way OWI-lab discovered that for a large number of sites the actual resonance frequencies were well above the as designed values. In this case the results were used to update the design for the next phase of the wind farm.

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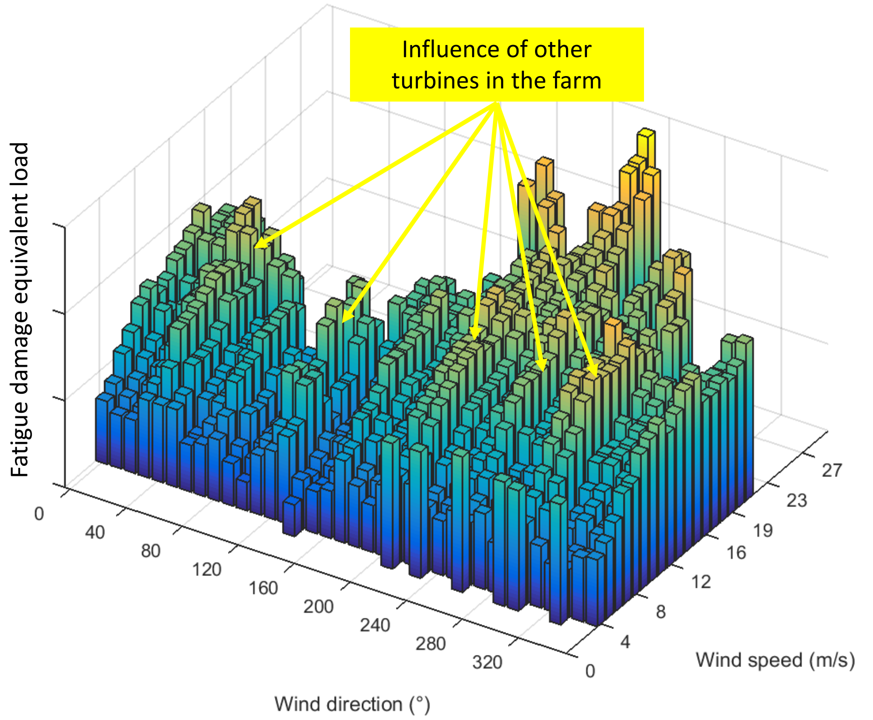


**Taking a look at fatigue**

Besides the development of scour the overall integrity of the substructure is vital in the decision support for offshore wind operators. Current design life of offshore wind farms ranges from 20 to 25 years, with some farms even targeting 30 years of operational use.

For monopiles, which represent the vast majority of current substructures, this design life is driven by the fatigue life of the welded connections. When the topic of life-time extension is raised it will be an added value when the operator knows the consumed fatigue life of the substructure. The most targeted approach to acquire such knowledge is to monitor and interpret the loads exerted on the substructure.

OWI-lab started performing load assessments in 2014 at the Belgian offshore wind farms. These load assessments involved the installation of strain gauges, either electrical or optical, at the interface level between the wind turbine tower and the substructure. These strain gauges record the stress and strain passing from the wind turbine into the foundation. The so-called interface loads are then calculated from the measurements.

The choice for the position just beneath the tower serves to compare the measured loads with the interface loads provided by the designers and the wind turbine OEM. The results allow identifying potential mismatches between design and operational conditions. When interface loads exceed design this can then trigger maintenance on the wind turbine. Or when loads are below design it opens the door for potential life time extension of the turbine near end-of-life.

Besides loads also the fatigue damage is quantified using the load assessment set-up. This serves to quantify the effect of wake effects on the fatigue damage. In the illustration provided actual measurements of the fatigue damage equivalent load are given for a Belgian offshore wind turbine using a year's worth of measurements. One can clearly see valleys and ridges in this graph. Hinting at wind directions with a reduced fatigue load compared to other directions. For these wind directions the turbine is facing outside the farm, receiving the clean non-turbulent air. For the other wind directions the turbine is directly behind another turbine in the farm and is subjected to more turbulent air.

Using this map of fatigue damage can help to assess the severity of the wake, which is also considered in design and serve as a decision tool in fatigue life assessment. It can also serve to quantify the wake effect when a new wind farm is constructed nearby.

However, fatigue of the substructure is not driven purely by the wind, wave and site conditions. The operational condition of the wind turbine also plays a vital role. For instance fatigue progression differs between parked and rotating turbines. These operational factors can change quite quickly over time. E.g. a turbine that due to a sudden malfunction performs an excessive amount of rotor stops, or shows a large rotor unbalance will inevitably be subjected to more fatigue damage. However, only through continuous measurements it is possible to quantify these effects on the remaining lifetime of a machine.

## Reducing sensors, using existing data

While the added value of a structural monitoring system on a wind turbine is clear, it is unrealistic to believe that every turbine in the farm will be equipped with these sensors. As such OWI-lab is investing heavily to reduce the number of required sensors, while still providing sufficient information to the operator. One development targeted at this is the virtual sensing concept. Virtual sensors use measurements from existing sensors and a simplified model to estimate the behaviour at different locations.

A key example is the development of a SCADA based load reconstruction. By using the high-frequent SCADA data and the measurements at an instrumented turbine it is possible to train a model that links the interface loads to the SCADA data.

Once this model is established the (partial) load history at every turbine can be reconstructed using only the information already captured by the SCADA system.

This information can then be used to perform a farm-wide load assessment and determine the fatigue damage of each turbine in the farm.


The long-term R&D efforts on the topic of structural health monitoring and structural integrity in the Belgian North Sea performed by OWI-Lab was rewarded recently at the WindEurope Offshore Conference 2017 in London. Dr. Ir. Wout Weijtjens was granted the 'Best R&D poster award' in the category 'turbine technology'. The rewarded R&D poster can be downloaded from www.owi-lab.be.

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