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Offshore wind turbine foundation monitoring, extrapolating fatigue measurements from fleet leaders to the entire wind farm

Wout Weijtens, Nymfa Noppe, Tim Verbelen, Alexandros Iliopoulos,
Christof Devriendt

OWI-lab, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium

E-mail: wweijtje@vub.ac.be

Abstract. The present contribution is part of the ongoing development of a fatigue assessment strategy driven purely on in-situ measurements on operational wind turbines. The primary objective is to estimate the remaining life time of existing wind farms and individual turbines by instrumenting part of the farm with a load monitoring setup. This load monitoring setup allows to measure interface loads and local stress histories. This contribution will briefly discuss how these load measurements can be translated into fatigue assessment of the instrumented turbine. However, due to different conditions at the wind farm, such as turbulence, differences in water depth and foundation design this turbine will not be fully representable for all turbines in the farm.

In this paper we will use the load measurements on two offshore wind turbines in the Northwind offshore wind farm to discuss fatigue progression in an operational wind farm. By calculating the damage equivalent loads on the two turbines the fatigue progression is quantified for every 10 minute interval and can be analyzed against turbulence and site conditions. In future work these results will be used to predict the fatigue life progression in the entire farm.

1. Introduction

Offshore wind is developing in Europe at a rapid pace, with ever growing turbine sizes and greater distances to shore the demand for structural monitoring of the substructures has become more relevant than ever. Currently there are just a limited number of designs in offshore wind used for substructures. Most used is the so called monopile foundation, in essence a single pile driven into the seabed. At the end of 2015 monopiles represented 80.1% of the total installed wind turbine capacity offshore [1]. Moreover, in 2015 97% of the newly installed offshore windturbines used monopile substructures. The remaining 3% of installed substructures in 2015 were jackets. Jackets are lattice structures which can be favorable in large water depths and at sites with strong wave action. Other foundation types such as gravity based, tri-pod and tri-pile foundations have been installed in the past but represent a far smaller population.

Most foundations for offshore wind are designed to withstand a given life-time, typically 20 to 30 years, without the need for any inspection or maintenance. Nonetheless there are several reasons that operators want to keep track of their substructures. For offshore wind turbines on monopile foundations fatigue life is a design driver [2, 3, 4]. This implies that in future decisions about maintenance, life-time extension or re-powering, the consumed fatigue life needs to be



taken into consideration.

Complimentary to a simulation-driven analysis, OWI-lab is developing a measurement driven fatigue monitoring concept to measure and assess the progression of fatigue in an operational wind farm. The proposed concept uses a limited number of turbines, called fleet leaders, instrumented to measure the load history of the substructure. The recorded load histories allow to determine 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.

2. Fatigue Monitoring

2.1. Measurement setup

In this contribution results from a measurement campaign in the Northwind offshore wind farm will be used. Northwind is the third Belgian offshore wind farm and lies approx. 37km from the coast of Belgium, Figure 1.(a). The Northwind wind farm consists of 72 Vestas V112-3MW turbines on monopile foundations with water depths ranging from 16m to 29m.

The measurement campaign started in October 2014 and is currently ongoing. Two turbines, Figure. 1.(b), were instrumented by OWI-lab after construction of the farm was completed. The turbines were chosen based on their position at the outer edges of the farm. Turbines at the outer edge are best suited to act as fleet leaders since they are subjected to both clean non-turbulent air as well as turbulent air coming from other turbines in the farm. As such turbines at the edge allow to directly measure the impact of turbulent air on fatigue loads, this allows to also draw conclusions about turbines in the middle of the farm. The second criterium for the choice of fleet leaders was the difference in water depth between the two turbines, Table. 1.

In the current project only 2 turbines were instrumented, this is the minimum number of fleet leaders required. A single fleet leader does not allow to verify the extrapolation to the entire farm. It is beneficial to the technique to increase the number of fleet leaders, or to instrument additional turbines with a reduced setup. However, this will increase the cost of the monitoring campaign.

At Northwind both turbines are instrumented with 2 accelerometers at three levels and 7 strain gauges spread over two different levels, Figure. 1.(c). The levels chosen for the strain gauges are the interface between the tower and transition piece and the interface between transition piece and monopile. The strain gauges are configured as such that they allow to determine the bending moments at these interface levels. In the continuation of this paper we will focus on the results from the interface between tower and transition piece.

The Northwind setup uses fiber Bragg gratings (FBG) as strain gauges either welded to or glued to the wall, Figure. 1.(d). A discussion on the differences between these two different types of connection can be found in [5].

2.2. Fleet leader concept

The fleet leader concept was first introduced in [6] as a cost-effective tool to monitor the blades of an offshore wind farm. The key idea behind the fleet leader concept is to instrument a limited number of wind turbines with an load monitoring setup, the so called fleet leaders. The results from these fleet leaders are then extrapolated to the entire wind farm.

Figure 2 shows the envisioned concept for the monitoring of offshore wind turbines substructures. The concept is general for all types of substructures, be it monopiles, jackets or tripods. The key idea is that the fleet leader measurements allow to assess the hot spot stress, for instance by using virtual sensing [8, 9]. In a second step these hot spot stresses allow to get to a fatigue assessment for the fleet leader itself. This fatigue assessment can be performed in a variety of ways. For instance (probabilistic) fatigue crack propagation, using Paris' law, or classic rain flow counting and S-N curves can be used. Rain-flow counting translates the

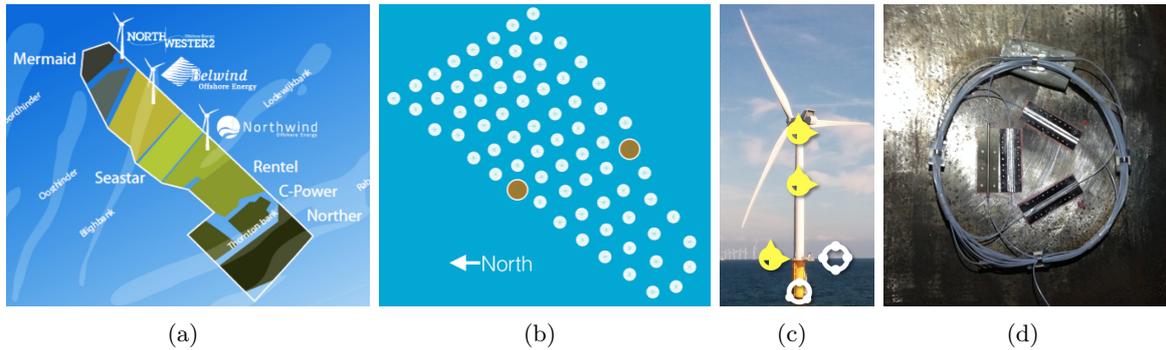


Figure 1. (a) Position of Northwind within the Belgian zone for offshore wind energy (b) Lay-out of the Northwind farm with the two fleet leaders high-lighted. (c) Northwind V112 Turbine with indication of accelerometers (yellow) and optical fiber strain gauges (white). (d) Optical strain gauges welded to the transition piece.

Table 1. Relevant properties of the two considered turbines. The resonance frequencies were determined using operational modal analysis [7].

	D06	H05
Design. Waterdepth (m)	26.9	18.9
Resonance freq. (Hz)	0.27	0.30
Turbine	Vestas V112	
Hub height (m)	71	
Monopile diameter (m)	5.2	

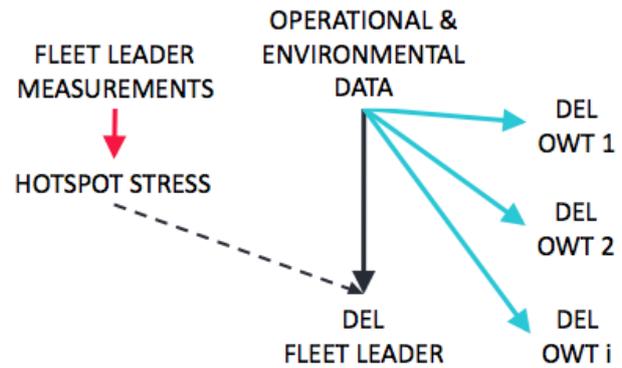


Figure 2. The fleet leader concept uses a heavily instrumented wind turbine and SCADA to perform a farm-wide fatigue assessment.

recorded strain histories into so-called fatigue spectra, also known as stress histograms. A fatigue spectrum provides the number of cycles n_i at a given stress range σ_i . The fatigue spectrum, is translated into a damage ratio assuming the linear Miner's rule [10].

$$\sum_{i=1} \frac{n_i}{N_i} = \sum_{i=1} C_i = C \quad (1)$$

in which C is the accumulated damage. If C equals 1 the structure is assumed to fail under fatigue. N_i are the number of allowable cycles of a specific material subjected to the stress range σ_i . The values of N_i are defined using so-called S-N curves. It is key to consider the correct S-N curve, stress concentration- and safety factors for each structural component and location during the fatigue assessment. The values of C therefore differ immensely for the considered S-N curve, and a damage value has no real meaning unless the S-N curve is clearly documented. The S-N curves themselves are typically set by the normative body. However, for offshore wind these S-N curves have been under discussion as they were built up over 40 years ago considering steel and welding conditions of that day [11]. Modern welders and steel manufactures achieve far better fatigue properties and research projects have been set up to update the S-N curves. An oddity of the Miner's rule in Eq. (1) is the linear sum. Basically, it calculates the damage

induced by each stress range σ_i and assumes the total damage is a linear combination of these individual contributions C_i . It therefore does not consider the sequence of different fatigue loads over time.

The found damage C has a very large range of values, making it hard to interpret on a linear scale. Therefore often the damage equivalent load DEL is calculated as a more linear measure for damage. The DEL is basically a hypothetical load with a fixed number of cycles N_{eq} and a fixed amplitude that introduces as much damage as the recorded more complex load history. For a S-N curve with a constant slope the DEL can be calculated using a single equation [12]:

$$N_i = k \cdot \sigma_i^{-m} \quad (2)$$

the DEL is directly found as :

$$DEL = \left(\sum_{i=1} \frac{n_i \sigma_i^m}{N_{eq}} \right)^{1/m} \quad (3)$$

A similar equation does not exist for S-N curves with different slopes, e.g. the S-N curves in air of DNV RP-C203 [13]. However, lack of a single equation does not imply one can not calculate the DEL for such a curve. A work-around is possible by first calculating the damage and then determining which part of the S-N curve will apply to the DEL.

Throughout this publication the DEL will be calculated from the Fore-Aft bending moment parallel to the wind direction using $m = 4$ and $N_{eq} = 10^7$. Due to confidentiality only normalized values can be shown.

The found DEL of the fleet leaders are linked to the operational conditions, to assess fatigue progression over the entire operational window. This covers both differences in wind direction, wind speed but also different operational regimes and wave conditions. All of this data is found either in the turbine SCADA or the wave radar(s) in the farm. Figure. 3 shows the outcome from such an analysis for an operational turbine. The results show different DEL for different wind sectors and wind speeds, a.k.a. bins. Note that some bins remain empty as some combinations of wind speed and wind direction have not yet occurred during the measurement campaign and are even unlikely to happen over the entire life of the turbine. Of particular interest is the valley that occurs from 80 to 230 degrees, in which the DEL is much lower than other wind directions. Figure. 3.(b) zooms in on this valley by showing the DEL for a single wind speed bin. These wind directions correspond with the wind directions for which this particular turbine is directed outside the farm. For these wind direction the turbine receives non turbulent air. In the other wind directions the DEL is elevated as the wind has already passed several other turbines and has become more turbulent. For $m = 4$ the DEL at this wind speed is up to twice as large when behind other turbines, compared to the clean air conditions. This observation is especially relevant to turbines in the middle of the farm, which are always subjected to turbulent air. From these results one can move on to a remaining useful lifetime (RUL) estimation by factoring in the probability of each bin over the 20 year life time.

The final step of the fleet leader concept is to extrapolate the results from the fleet leaders to the entire farm. To do so a model needs to be built for the fleet leaders that relates the DEL to the different parameters found in the SCADA and the wave radar. This final step will be discussed in more detail in the next section.

3. Farm wide assessment

In the farm wide assessment the results from the fleet leaders are extrapolated to the entire farm of turbines. This extrapolation will need to properly factor in the differences between turbines in the farm. One possible cause of these differences are the different wind conditions in the farm. Effectively, Figure. 3 showed that turbulence will play a role in the fatigue life progression

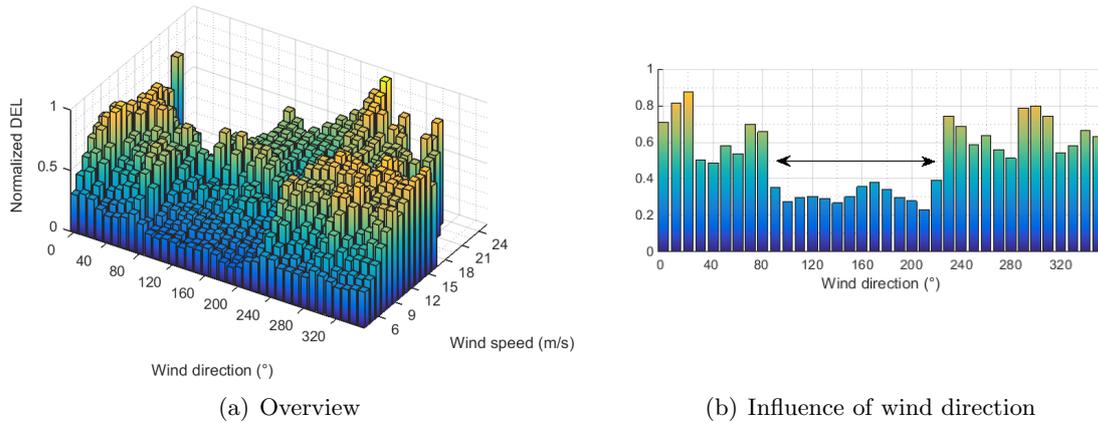


Figure 3. DEL for different wind sectors. (a) Overview of all wind sectors and wind speed. (b) Detailed view for one wind speed bin (7-8 m/s) reveals the dependency on the wind direction.

of turbines. Another source of different fatigue progression in the farm are the differences in structural dynamics. Table 1 shows that the two monitored turbines in the farm have different resonance frequencies.

Finally, also the overall availability and condition of the turbine will play a role in fatigue life. The hours spent in parked, downrated, curtailed conditions due to maintenance will influence the DEL and RUL [3]. Other maintenance related properties, like increased rotor loads, e.g. due mass unbalance, or excessive number of start-stops can accelerate fatigue progression but are outside the scope of the current paper.

To cover all these variabilities the aim of the current (ongoing) project is to assess the DEL for any turbine i in the farm using following simplified model :

$$DEL_i = SSP(f_{res,i}, D_{MP,i}, H_s, T_p) \cdot \xi_{FL}(I_i) \cdot DEL_{FL}(U_i, P_i) \quad (4)$$

in which $SSP(f_{res,i}, D_{MP}, H_s, T_p)$ is a site specific parameter that will cover the difference in DEL due to the different structural/dynamic properties of each turbine and was inspired by [14]. The SSP is a function of the turbine's resonance frequency $f_{res,i}$. The resonance frequency is considered as the driving parameter of fatigue life. As a single parameter the resonance frequency directly relates to the number of cycles, the stress ranges and the susceptibility to wave and harmonic excitation of the entire substructure. The resonance frequency depends on the soil properties, water depth and overall weight of the entire offshore wind turbine. However, several experimental results [15, 16] have already shown that the resonance frequencies measured offshore differ from those calculated in design. Moreover, since the resonance frequencies of turbines can accurately be measured [16] after installation, it is chosen to include the resonance frequency directly into the model.

In addition properties related to the wave loads like the monopile diameter D_{MP} and wave energy spectrum parameters : significant wave height H_s and peak wave period T_p will play a role in the SSP .

In contrast DEL_{FL} is a model, trained on the fleet leaders, that relates the DEL to SCADA parameters such as wind speed U and power output P . In essence such a simple model is already shown in Figure. 3.(a). Similarly the turbulence factor ξ_{FL} will model the effect of turbulence, in particular caused by other turbines in the farm, using the turbulence intensity I_i . Assuming all turbines are identical ξ_{FL} and DEL_{FL} can be carried over to all turbines by just using the

SCADA of the considered turbine.

At this point the model in Eq.(4) is still under development and might expand over time. But the remainder of this paper will discuss and motivate the current elements of the model. In Section 3.1 the DEL_{FL} will be discussed, Section 3.2 will discuss the necessity for the SSP .

3.1. SCADA based model

3.1.1. *Turbulence* Figure. 3.(b) already clearly revealed the link between DEL and turbulence. To model this link the turbulence intensity can be derived from SCADA as :

$$I = \frac{\sigma_U}{U} \quad (5)$$

with σ_U the ten-minute standard deviation of U . However, earlier research already revealed the unreliability of the wind turbine anemometer to accurately determine the wind speed and turbulence intensity at the turbine [17]. Future research will therefore also focus on using all SCADA data or models to determine a more accurate turbulence intensity. In this contribution Eq. (5) is used.

To analyse the effect of turbulence on the DEL all measurements are binned for different turbulence intensities and normalized with the DEL corresponding with a wind sector for which the turbine is not behind any other turbine in the farm and thus is not subjected to turbulent air. The resulting turbulence factor ξ is thus a dimensionless number that indicates the increase in DEL for different turbulence intensities. Results for both fleet leaders, D06 and H05, are shown in Figure. 4. A clear trend is visible as the turbulence factor increases for increasing levels of turbulence intensity.

The idea is to use these turbulence factors and the measured turbulence intensities I_i on each turbine i to factor in the effect of turbulence on each turbine in the farm. As a proof of concept Figure. 4.(c) shows the measured DEL at D06 along with the estimated DEL based on ξ_{D06} and ξ_{H05} . This results proofs the concept to use the turbulence intensity as a metric to factor in turbulence effects and shows that it is permissible to use a model trained on another turbine to predict the DEL.

The full result when the DEL of D06 are predicted using ξ_{H05} for all wind speeds is shown in Figure. 5. The model definitely is not perfect, which is no surprise given the differences between Figure. 4.(a) and (b), but the results motivate to further develop this approach.

3.1.2. *Availability* With increasing turbine weights and monopile diameters the importance of wave loading on fatigue life has increased considerably. Given the low damping in parked conditions [18], it has been observed that for some (extra-)large monopile designs the majority of fatigue damage is accumulated during parked conditions even though the turbine was only parked for 3% of the total time [3].

As a consequence one will need to factor in the time spent in parked conditions for each turbine. The time spent in parked conditions can be determined from the combination of wind speed and power output, both parameters are by default part of the SCADAS data of any wind turbine.

3.1.3. *Events* Events will play a role in the fatigue life of the offshore wind turbine. While some events are hard to track, such as slamming waves and boat landings, others can be readily observed using the turbine SCADA.

With respect to fatigue one of the strongest events observed on an offshore wind turbine are rotor stops and rotor starts. A rotor stop either occurs manually, e.g. during maintenance, or automatically when the wind speed is larger than the so-called cut-out wind speed. When the wind speed is again below this cut-out speed, or the manual stop is ended, the turbine will again start up. A Stop-Start cycle implies a near immediate drop of the thrust load and a fast

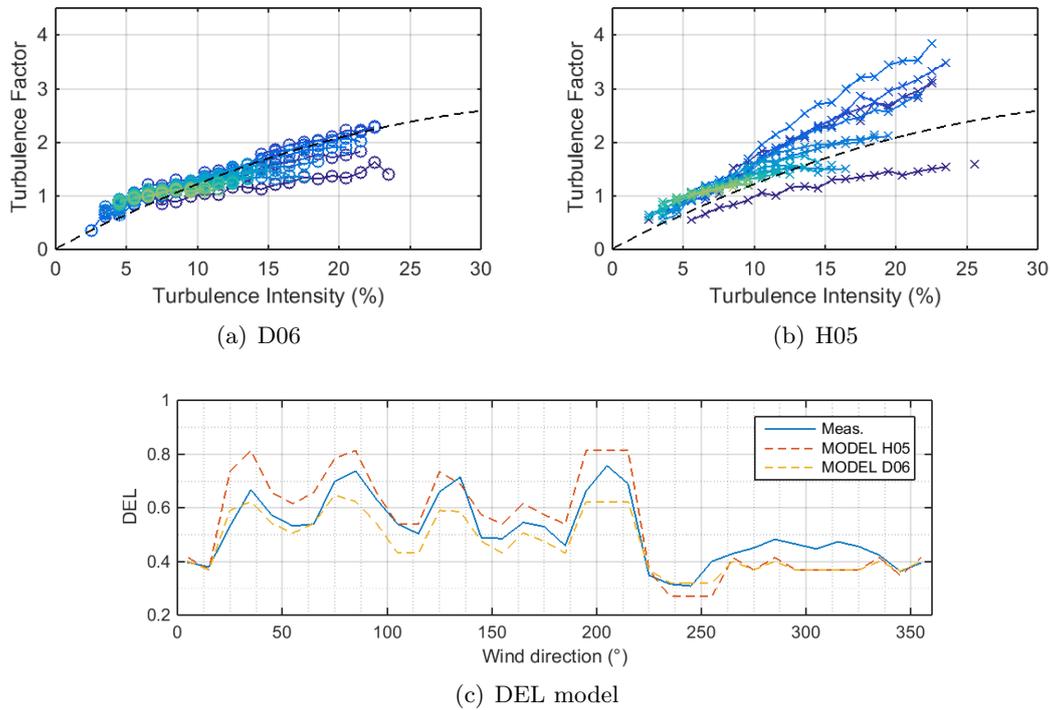


Figure 4. (a-b) Turbulence factor of the DEL for different wind speeds (low wind : dark, strong wind : light). (c) The turbulence intensity is used to model the DEL for D06. Both a model trained on D06 and H05 captures the effect of other turbines in the farm, results shown for 6-7 m/s.

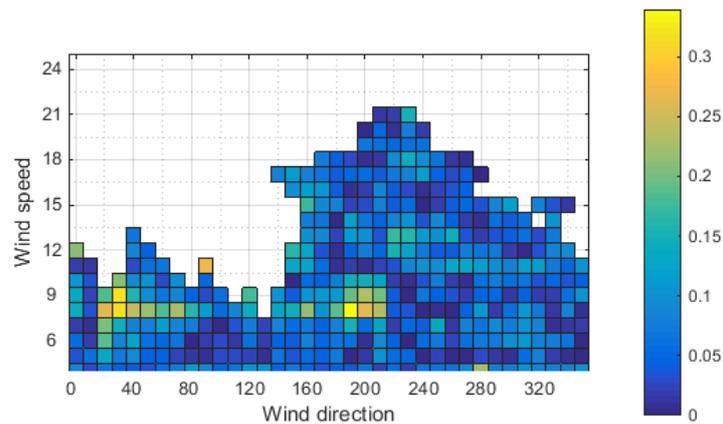


Figure 5. Absolute error of the predicted DEL with the normalized measured DEL.

build-up of the thrust loading afterwards, as shown in Figure. 6. While these events induce the largest stress ranges, their relative impact on the total consumed life time depends heavily on their occurrence and used S-N curve in the Palmgren-Miner rule.

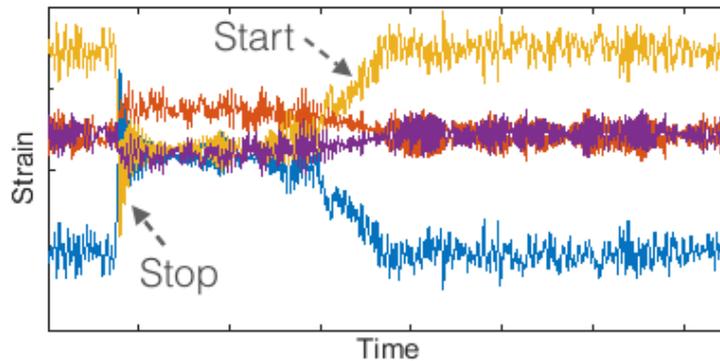


Figure 6. Measured strains at 4 headings at the interface level during a rotor stop and consecutive rotor start. During a rotor stop the thrust loading is quickly reduced, during the rotor start the thrust is built up.

3.2. Site specific parameter

In [19] a detailed analysis for the sensitivity of the DEL to different structural parameters was made. In particular the mean sea level (MSL) was confirmed to play a significant role in the DEL. With a greater MSL, and thus longer substructure, the resonance frequency decreases, making the structure more susceptible to wave loads. In general with increasing water depths and increasing nacelle weights, the resonance frequency of offshore turbines has been steadily decreasing over the past years. Due to the wave-structure interaction the structural dynamics are playing a growing role in the fatigue life of turbines. This also means that with different MSLs in the farm and thus different resonance frequencies fatigue life will progress differently for different turbines in the farm.

The concept of a site specific parameter was proposed in [14, 20] to model the fatigue behavior of individual monopile foundations subjected to wave loading. While it was mainly intended as a tool for design it is believed that this concept can be transferred to monitoring and the fleet leader concept.

When considering that the monopile diameter in Northwind is constant, the site specific parameter in [14] and Eq. (4) only depends on the resonance frequency.

At this point the concept of a site specific parameter used for monitoring is still under development. However, some lessons learned in [19, 14, 20] can be observed in the results of the current monitoring campaign. Figure. 7 shows the relation between the wave height and the DEL for both turbines when only non-turbulent wind directions are considered. As wave height is strongly correlated with the wind speed the data was filtered for a narrow wind speed range of 11m/s to 13 m/s. The near linear behavior is consistent with results in [19], which used the Airy wave theory.

In Figure. 8 the fatigue spectra are plotted for both turbines. Turbine D06 is subjected to slightly larger stress ranges than H05 as is consistent with its lower first resonance frequency, Table 1. This implies that D06 over time will accumulate fatigue damage faster than H05. The larger DEL for D06, which is at a larger water depth than H05 (Table 1), is consistent with the simulated results described in [19]. An additional observation is that the second lobe of D06 has larger stress ranges than the second lobe of H05. This can be motivated by the second order resonance frequency which is considerably smaller for D06.

The prior analysis always assumed that the environmental conditions are similar in the entire farm. This implies that every turbine will see the same statistical wave load over its entire life-time. This assumption might no longer be valid for farms with large variations in water depths over the area of the farm.

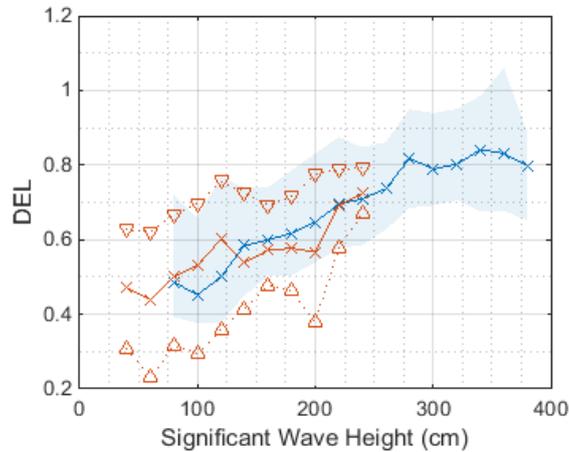


Figure 7. Median DEL versus the significant wave height (x) for both NWD06 (blue) and NWH05 (red) in non-turbulent wind directions. Results shown for wind speeds from 11 to 13 m/s. The blue surface indicates the 10th to 90th - percentile interval of NWD06, for NWH05 this interval is indicated with triangles.

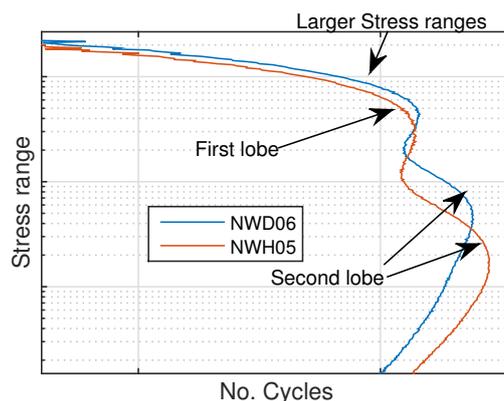


Figure 8. Fatigue spectra for both instrumented turbines, results at rated power and for wind directions both turbines are in non-turbulent air.

4. Conclusion

In this paper the challenges for a farm wide fatigue assessment are discussed. The proposed approach is the fleet leader concept, in which a limited number of representative turbines are instrumented with accelerometers and strain gauges. The results from these turbines are extrapolated to the entire farm using an empirical formula.

Based on the initial results from the ongoing monitoring campaign at the Northwind offshore wind farm two main conclusions are drawn.

- Turbulence will play an important role in farm wide fatigue assessment. A proof of concept in this paper shows that the results from fleet leaders are likely transferable to other turbines in the farm.
- Site specific dynamics need to be factored in, especially for farms with large monopile

diameters where wave loads become dominant.

It is concluded that the fleet-leader is a viable research goal but still requires continued research. Future research will mainly focus on further fine-tuning the Site Specific parameter for assessing the farm wide fatigue progression.

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