MONITORING THE CONSUMED FATIGUE LIFE OF WIND TURBINES ON MONOPILE FOUNDATIONS

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Abstract :

Fatigue life is often a design driver for offshore wind turbines. A better understanding on the mechanisms behind fatigue can improve design and thus reduce the initial cost of future substructures. This contribution aims to improve the understanding of fatigue life progression through monitoring. Measurements on an existing structure allow linking the fatigue life progression to different operational and environmental conditions, which can then be returned as a design input. In addition a continuously monitored fatigue life can serve an important role in deciding over wind farm inspections, repowering or lifetime extension.

This paper introduces the OWI-lab fatigue monitoring strategy and uses data from three instrumented turbines outside the Belgian coast to illustrate the impact environmental and operational conditions have on the consumption of fatigue life. The ultimate goal is to use the observed relations to build a toolbox which will allow to perform farm-wide fatigue assessment.

1   Introduction

Fatigue life is a design driver for offshore wind turbines and a key concern of wind farm operators. Most monitoring campaigns that are currently performed are often related to fatigue life. A good example is scour monitoring. Yet the major concern is not the scour itself, but rather the effect scour has on the turbine dynamics (e.g. the max bending moments) and ultimately the designed (fatigue) lifetime [1]. But even when scour is detected one still needs to analyse to what extent the fatigue life is affected.

An alternative approach is to directly monitor fatigue life consumption, e.g. by measuring the loads experienced by the turbine. This allows to track the consumption over time of fatigue life, but also allows to put actual results against design assumptions. In collaboration with designers and regulatory bodies this can result in improved design codes in the near feature. The results from a fatigue monitoring campaign can also serve as a support tool for cost-effective inspection and
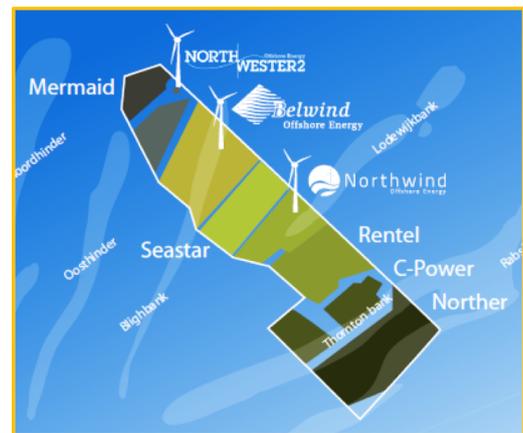
Figure 1: Location of the Belwind and Northwind wind farms

end-of-life decision for the wind farm owner. By better understanding how fatigue is progressing for the different turbines within the farm, the owner is better aware of turbines that might run up to their expected lifetime and turbine that can be considered for lifetime extension.

This paper is part of an ongoing research collaboration between the Vrije Universiteit Brussels, OWI-lab and Parkwind, the owner of the Belwind and Northwind offshore wind farms outside the Belgian coast, Fig. 1. The main goal of this research collaboration was to develop and field-test a broad monitoring strategy for offshore wind turbines that can support wind farm owners and developers in the near future. To develop a monitoring strategy for offshore wind turbines on monopile foundations one turbine at Belwind, a farm consisting of 55 Vestas V90 turbines on monopiles, was equipped with a multi physics sensor array in 2012. This sensor array ranges from LVDT's and force transducers to monitor the condition of the grouted connection, accelerometers for dynamic analysis and corrosion sensors in the monopile. At the more recent Northwind wind farm, 72 Vestas V112 on monopiles, two turbines were equipped with an optimized setup. The three equipped turbines are currently continuously monitored.

The data from these monitored turbines, in combination with state of the art data-processing, has resulted in a large database of over 3 years of
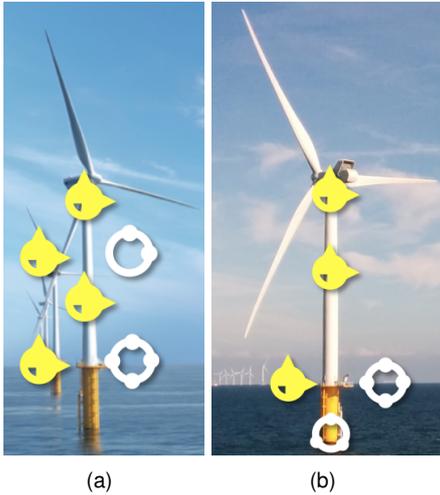
Figure 2: (a) Belwind V90 turbine (b) Northwind V112 Turbine with indication of accelerometers (yellow) and optical fiber strain gauges locations (white)

relevant dynamic properties and amongst others an in-depth analysis of the damping properties of offshore turbines [2,3].

2 Methodology

In the following section the measurement setup for fatigue monitoring will be explained and the proposed monitoring strategy will be introduced.

2.1 Measurement setup

In early 2014 optical strain gauges, a.k.a. fiber Bragg gratings [4], were added to the Belwind setup. Two strain gauges at the middle tower level and four sensors at the tower-Transition Piece (TP) interface connection, Fig. 2.(a). The array of four sensors at the tower-TP interface is equally distributed over the entire circumference of the tower. This setup allows, after calibration, to determine the instantaneous bending moment at the interface level as well as the direction of the bending moment.

At Northwind two turbines are equipped with a similar setup as at Belwind, Fig. 2.(b). Particular for Northwind is the addition of nine optical strain gauges at the TP-Monopile interface. The optical strain gauges are installed in three rosettes, which are equally spaced over the circumference of the TP-wall. This setup allows to identify both the tower bending moment as well as the torsional moment at the monopile interface level. Each rosette is accompanied by an additional optical temperature sensor to compensate for temperature effects.

To assess the results it is necessary to have an insight into the operational and environmental conditions at the site. To allow this a subset of the turbines' SCADA is made available by the wind farm owner. In addition meteorological data is available
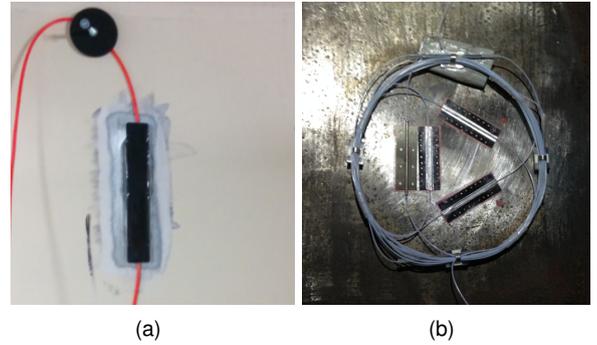
Figure 3: Optical strain gauges as installed at (a) Belwind and (b) Northwind prior to applying the protective sealing. Northwind features a rosette setup at the TP-MP interface which allows to determine tower bending as well as tower torsion. The fourth sensor in the rosette serves to compensate the temperature variation of the optical fiber strain gauge.

from a meteorological station on top of the Belwind OHVS and two wave radars installed at Belwind.

2.2 Monitoring the consumed fatigue life

The concept of the proposed fatigue monitoring strategy is summarized in Fig. 4. The key idea is to develop a strategy that requires a limited number of instrumented turbines spread across the wind farm and to extrapolate the results from these turbines to the entire wind farm. An approach that also has been suggested in [5]. However, applying such an extrapolation to monitor the foundation fatigue life requires a proper understanding of the relation between operational and environmental conditions and the consumption of fatigue life. In particular the differences in turbine dynamics and availability of each individual turbine will directly influence its fatigue life. A well known example is the potential interaction of waves with the turbines' first resonance frequency, which potentially reduces the turbine's useful life. To avoid this interaction is often the motivation for scour monitoring or scour protection.

In this contribution we will focus on the cycle counting histograms, a.k.a. fatigue spectra, of the tower bending moments as a tool to understand the mechanisms behind the consumption of fatigue life. These cycle counts can in the future be translated into damage indices and ultimately consumed lifetime using industry accepted methods such as Miner's rule and the appropriate S/N curves. In addition stress concentration factors need to be taken into account to incorporate the effect of structural features such as welds and bolts.

2.3 Interpreting long term results

To assume a worst case scenario with respect to fatigue life we will count the cycles for the bending-
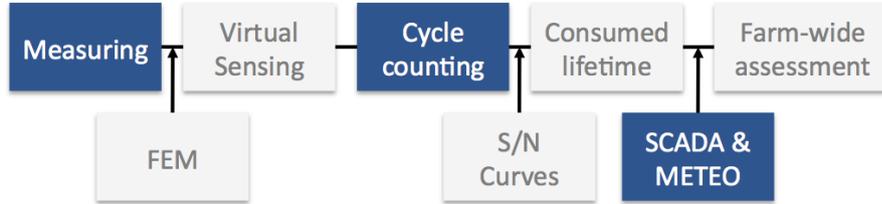
Figure 4: Overview of the fatigue monitoring strategy as proposed by OWI-lab. In this contribution we will focus on how environmental and operational conditions will ultimately affect fatigue life.
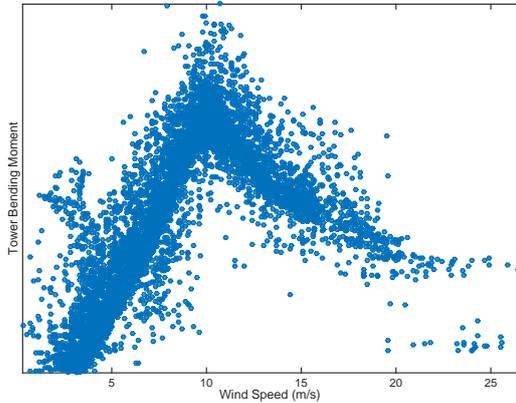
Figure 5: Tower bending at the Tower-MP interface vs. the wind speed at one of the Northwind turbines.

Table 1: Used case definitions for the V112

▇	Parked
▇	Parked idling
▇	Operating : Run-up
▇	Operating : Max. RPM
▇	Operating : Max. Power

moment equivalent stress, Fig. 5.

All available ten-minute records of these equivalent stresses are processed using rain flow counting. This returns a histogram that summarizes the number of cycles for a given amplitude. We can interpret these results by putting them against the relevant S/N curve.

However, to better understand the effect of different operational conditions the datasets are divided into different operational cases. The cycle counting histograms can then be built for each case individually. In the next section this analysis will be demonstrated.

2.4 Effect of operational conditions

The case definitions used for the V112 in this contribution are shown in Table 1. Fig. 6.(a) shows a cycle counting histogram of one of the Northwind turbines. This plot shows the cycle counting histogram for the most recurring operational cases. Obviously, operational cases of power production occur far more often and will ultimately contribute the most to the consumed fatigue life. This can also be seen in Fig. 6.(a) in which the number of cycles during operation far exceed those associated with parked

conditions. However, to better understand the mechanics driving fatigue these histograms can also be normalized w.r.t. the time spent in each operational case. This allows to build a plot in which each histogram is the histogram of a turbine that would spend an entire year in each operational case. Such a normalized result is shown in Fig. 6.(b) for the second Northwind turbine.

Fig. 6 reveals interesting behavior in the mecha-
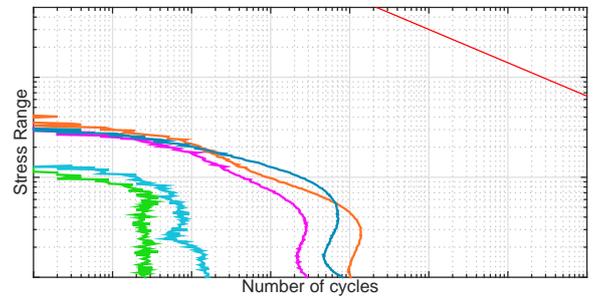
(a) Non normalized Northwind D06
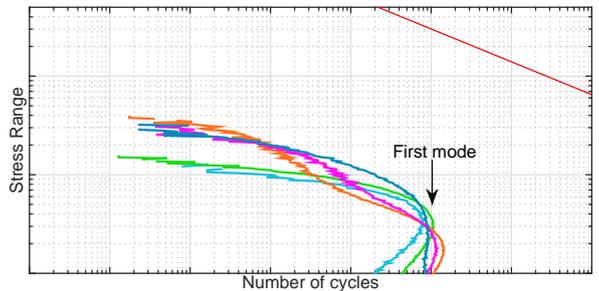
(b) Normalized Northwind H05

Figure 6: Cycle plot histograms, a.k.a fatigue spectra, for the most occurring operational cases. Colors correspond do the different operational cases as defined in Table 1. In red a S/N curve is added as example. (a) The total contribution to damage strongly depends on the time spent in each operational case. (b) Normalizing the cycle histograms w.r.t. the time spent in each operational case reveals the different mechanics of fatigue for different operational cases.

nisms of fatigue. In both plots a lobe in all operational cases is visible near the bottom of the graph. For the normalized graph, Fig. 6.(b), the (normalized) number of cycles is approximately equal for all operational cases. The driver behind these lobes is the first foundation mode of the turbine. As the first mode has a relatively fixed frequency the number of
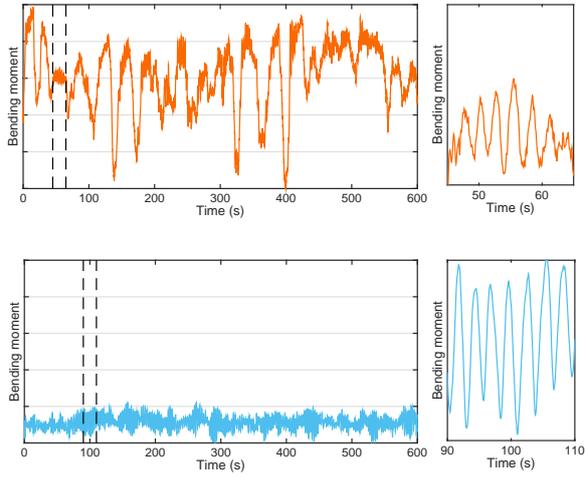
Figure 7: Example datasets of the instantaneous bending moment for both a (top) power producing and (bottom) a parked dataset. On the left a zoom on the time records reveal the oscillations related to the first order mode.

cycles is determined by this frequency rather than the operational condition. Nonetheless, the stress range of this lobe is larger during parked conditions than during power producing cases. In particular for the Parked (•) case and Run-up (•) this difference becomes apparent. As the mean wind speeds of these two operational cases during the considered period are comparable, respectively 7.29±2.62 m/s and 7.34±1.36 m/s, the difference in stress range cannot be attributed to different wind conditions. A possible explanation can be found in [2]. The damping of the first tower mode is far less during parked conditions (<2%) in comparison to the damping during rotating conditions (>5%). Less damping will ultimately result in larger cycles under the same (wind) excitation.

However, this does not imply that for these turbines fatigue is driven by the first mode in parked conditions. Fig. 6.(b) also reveals that power producing cases have an additional lobe above the contribution of the first mode. This lobe represent stress ranges that exceed those during parked conditions, but represent far less cycles. Nonetheless in a damage assessment these lobes will contribute significantly to the fatigue life, as they are closer to the SN curve. These large low frequent cycles are attributed to low frequent variations in the thrust loading of turbine that occur during normal operation of the turbine. Interestingly, these variations would not pop-up in ten minute averages of the SCADA and thus motivate measuring the actual bending moments.

Fig. 7 shows the instantaneous bending moments for both an operational and a parked dataset. The large low frequent variations in the bending moment are readily recognizable during power production and do not appear in the parked dataset.

As expected from the cycle histograms both

datasets do show the oscillations linked to the first tower mode. However, for parked conditions these oscillations are, on average, larger in amplitude and are the dominant cause of cycles in the bending moment.

Up to now the analysis was limited to the effect of operational conditions on fatigue life. Another key parameter that can affect fatigue are the environmental conditions at the site.

2.5 Effect of environmental conditions and environmental events

To asses the effect of environmental conditions on the fatigue life we can transform the cycle counts into an instantaneous damage rate using Miner's rule and a representative S/N curve. The instantaneous damage rates can then be analyzed against the available environmental parameters from the turbine SCADA or the wave radars.

An interesting observation is made when putting the instantaneous damage rate, during run-up, against the wind direction. Examples are shown in Fig. 8 for both a turbine in the middle of the windfarm and a turbine at the outer edge of the farm. Fig. 8.(a,b)

(a) Turbine in the middle of Belwind

(b) Turbine at the edge of Northwind

(c) Damage rate vs. turbulence intensity
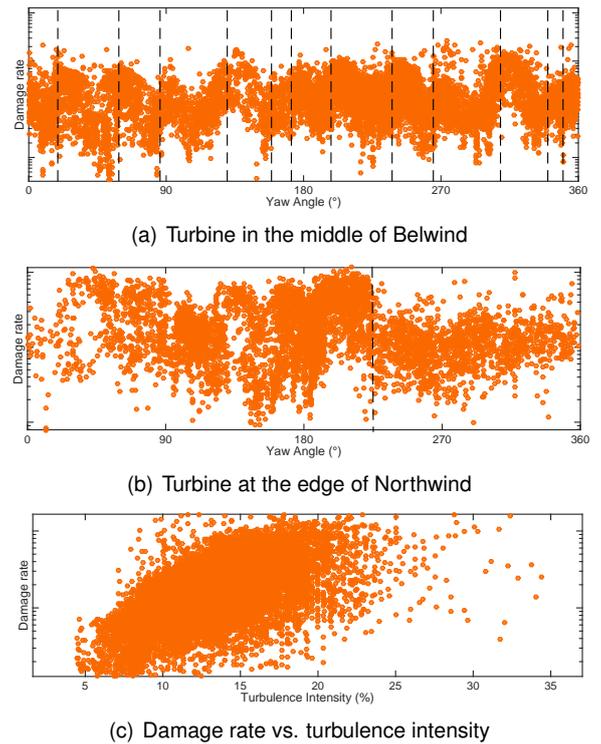
Figure 8: (a-b) Plotting the damage rates against the wind direction reveals that for several wind directions the damage rate has increased. (a) Wind directions in which a turbine is behind another turbine are marked with a dashed black line and show an increased damage rate. (b) As this turbine is at the outer edge of the wind farm the damage rate drops beyond 220 deg. as the turbine receives clean, non-turbulent air. (c) Turbulence intensity correlates with the increased damage rates

show that for given wind directions a distinctive increase in the instantaneous damage rate occurs. For the turbine in the center of the wind farm, Fig. 8.(a) each increased damage rate corresponds to a wind direction in which the turbine is in the turbulent air of another turbine in the farm. For the turbine at the edge of the park a similar observation can be made. Beyond 220 deg. the turbine is facing outside the farm and thus receives non-turbulent air. Exactly in these wind directions the damage rates have significantly dropped.

The observation that an increased damage rate can be attributed to the turbulent air is key in this analysis. Consequently any fatigue assessment model should properly include the turbulence intensity as a parameter. This also implies that the dominant wind direction at a wind farm is a driving parameter of fatigue life. In essence a turbine that is receiving turbulent air in the dominant wind direction will fatigue faster than one that is not subjected to turbulent air. Note however, that at this point we are only assessing fatigue rates and a definitive conclusion can only be made when a reliable assessment of the remaining useful life is made.

3 Future work

The most important future work is to translate the cycle counting histograms into a reliable estimation of remaining useful life.

3.1 Reliable remaining life assessment

In order to obtain a reliable assessment of remaining life the analyst needs to take into account the lessons learned from this analysis. A remaining useful life needs to take the different operational conditions into consideration as well as their expected occurrence in the future.

In addition any calculation of the remaining useful life needs to consider the stochastic nature of the S/N curve and the predicted site conditions and define uncertainty bounds accordingly. Moreover, it will need to take into account the effect of (stochastic) short-term events, like wave-slams, boat-landings and (emergency) stops. For instance in Fig. 9 recent results, from our participation in the WiFi project [6], are shown for the BBC01 turbine in which two wave impacts occur. The effect of these slamming waves on fatigue life needs to be investigated and when necessary added to a fatigue assessment.

3.2 Virtual Sensing

All prior analysis assumes that the installed strain gauges are attached to the fatigue hotspots, which is not always feasible.

For monopile foundation the fatigue hotspot is often situated below the sea-level at the mudline of the
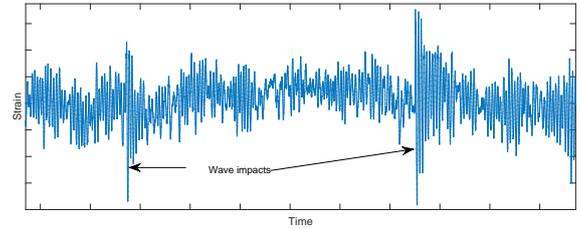
Figure 9: Strains measured during two confirmed wave impacts. A reliable remaining lifetime assessment will need to take into account the occurrence of these environmental events.

foundation. In practice this implies the installation of strain gauges on the monopile prior to the pile driving. It also becomes difficult to maintain these submerged sensors throughout the operational life of the turbine.

To resolve the limitations of direct measurement of hotspot stress, virtual sensing techniques are looked into. Virtual sensing allows to use accelerometers installed in the tower to predict the strains at any virtual sensor locations, e.g. the mudline or at the node of a jacket foundation, using the turbine's Finite Element Model. Accelerometers in the tower are far more reliable than submerged strain gauges and are easier to maintain. Moreover, the installation of the necessary accelerometers can be done after completion of the OWT.

Currently, much research is invested [7, 8] to develop these techniques. But the step towards a method that is applicable over the full operational range of the turbine still needs to be taken. Future work at OWI-lab will therefore validate these techniques using the long-term data that is available from the ongoing monitoring campaign.

3.3 Farm-wide fatigue assessment

The final step is linking consumed life time to the operational and environmental parameters using data mining techniques. This will allow to determine the park-wide consumed life time with only a limited number of instrumented turbines, Fig. 4. However, such method will still require a good understanding of the mechanics of fatigue progression.

For instance this paper already showed the presence of the first mode in the cycle counting. Different turbines will have different resonance frequencies and ultimately age differently. To perform a farm wide fatigue assessment a model that incorporates the dynamic properties of each individual turbine will be necessary.

4 Conclusion

This paper introduced a fatigue monitoring strategy for offshore foundation based on measurements at three turbines in the Belgian North Sea. By combining results from strain gauges and operational and

Figure 10: The ultimate goal is to develop a toolbox to perform a farm-wide fatigue assessment based on measurements at a limited number of instrumented turbines

environmental parameters, we have shed a light on the different dynamics of fatigue life progression in operational turbines.

It showed that a reliable remaining useful life assessment will require to incorporate the different fatigue behavior under the different operational cases of the wind turbine. Moreover environmental events, like wave-impacts , or the influence of turbulent air need to be taken into consideration.

The current research continues and will aim to develop a reliable farm-wide fatigue assessment based on a limited number of instrumented sensors.

5 *Acknowledgements

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