Response to Reviewer 2

Title of paper: Structural monitoring for lifetime extension of offshore wind monopiles: Can strain measurements at one level tell us everything?

Dear Reviewer,

Thank you for the review of our submitted paper. We appreciate your constructive feedback and valuable comments on the topic. Please find below our suggestions, how we plan to modify the manuscript.

Please let us know if the suggested revisions fulfil your expectations.

Kind regards,

Lisa Ziegler - on behalf of the authors

03/07/2017

Review comments

The revision comments are organized as follows: The review comments are repeated in *italic*, responses are stated in normal black, and suggestion for revisions of the manuscript are shown in red.

General comments

Comment 1: The analysis focuses on the prediction of fatigue damage values at mudline in the monopile. How critical is this location in the overall fatigue loading of the structure? Monopiles are commonly build by a pile structure with transition piece as connection to the tubular tower. How does the transition piece with grouting connection influence the ability to predict/transfer fatigue loading values from above to below the transition piece? Does other structural components influence the accuracy of the model in terms of prediction of values at other locations?

For the monopile design of our case study, the welds near mudline have a high fatigue life. Thus, these welds will not limit the overall fatigue life of the structure. The accuracy of the extrapolation method improves the smaller the distance between measurement location and predicted location is. We presented the extrapolation to mudline as an example, as this has a challenging distance to the measurement location. The method works comparably for other locations along the structure.
We plan to add this explanation in Chapter 3.3 Discussion: The extrapolation method is exemplarily presented here from tower bottom to mudline. The algorithm was tested for other locations with comparable results (not shown here). The accuracy of the extrapolation method improves the smaller the distance between measurement and predicted location is.

We used a flanged connection of the transition piece to tower and monopile in this case study. Only the early designs of monopiles and transition pieces still had full grouted connections. In these cases, the grouted connection is typically modelled by distributed connecting elements. The process of FE model updating should verify that the global dynamic behaviour of the structure is captured correctly in the model. If omitted secondary steel elements are important for the global dynamics, added masses shall be included during the FE model update. Future work with measurement data is necessary to address FE model updating and the sensitivity of the extrapolation algorithm to this.
We plan to add an explanation in Chapter 3.1 Case study: Turbine and monopile were modelled in detail following industry state-of-art. The turbine tower is connected to the monopile with a flanged transition piece.
Additionally, we plan to give additional information on FE model updating in the newly inserted Chapter 2.3: The process of FE model updating should verify that the global dynamic behaviour of the structure is captured correctly in the simulation model. Typical model updating techniques try to match natural frequencies, mode shapes, and damping. Devriendt et al (2014) use data from distributed accelerometers for operational modal analysis of on offshore wind turbine. Maes et al. (2016) show that the first and second fore-aft and side-side natural frequencies of a monopile are identifiable from strain gauge measurements at the tower in operating conditions of the wind turbine by transforming strain time series into power spectral densities. Modern turbines are often equipped with accelerometers in the nacelle whose measurements can be beneficial for the model updating procedure. After identification of

the relevant modal properties, a sensitivity analysis should reveal which parameters in the original design model are uncertain and influential on the mismatched modal properties. For the case of the monopile support structure, these parameters can be, for instance, soil properties, manufacturing tolerances, grouted connection (early designs of transition pieces) and secondary steel elements if omitted in the initial FE model. Several methods exist to update the finite element model through minimization of an objective function addressing the selected parameters as described in standard literature (e.g. Friswell and Mottershead, 1995). The updating procedure should be repeated in time to identify possible changes on natural frequencies of the structure. Such changes could occur, for instance, due to scour or soil stiffening over time. Future work with measurement data is necessary to address FE model updating based on strain measurements for a monopile and the sensitivity of the extrapolation algorithm to this.

Devriendt, C., Weijtjens, W., El-Kafafy, M., & De Sitter, G. (2014). Monitoring resonant frequencies and damping values of an offshore wind turbine in parked conditions. *IET Renewable Power Generation, 8*(4), 433-441.

Friswell, M.I. and Mottershead, J.E. (1995). *Finite Element Model Updating in Structural Dynamics.* Netherlands: Kluwer Academic Publishers.

Comment 2: Does the method include the possibility to evaluate fatigue of soil bearing capacity based on measured loads, or is this out of scope?

We expect that it is possible to identify changes in soil conditions as soon as these affect the natural frequencies of the structure. This is part of FE model updating, which is left for future work.
We plan to mention this briefly in the newly inserted paragraph 2.3 FE model updating: FE model updating can be used to identify changes that possibly occur in soil conditions over time, such as soil stiffening, as soon as these changes have a measurable effect on the natural frequencies of the structure.

Comment 3: What is the common practice for LTE analyses in the wind industry by today? How are such analyses performed for other offshore structures, e.g. oil and gas platforms? I'm aware of that loads on these structures are substantially different from what wind turbines experience. However, LTE is common practice in this area and experience from such analyses could potentially be transferred to the wind industry.

We have currently a paper submitted to a journal, which reviews the state-of-art of lifetime extension practises for onshore wind turbines in four European countries. For further details, we refer the interested reader to this paper.

We plan to add some explanation in Chapter 1 Introduction: There is almost no experience with lifetime extension of offshore wind turbines yet. Vindeby, the first commercial offshore wind farm installed in 1991, was decommissioned recently after 25 years of operation. Other existing structures, e.g. bridges, offshore oil platforms, and lately onshore wind turbines, have dealt with lifetime extension for multiple years already. Lifetime extension assessments and decision making in the oil and gas industry is discussed by Ersdal & Hörnlund (2008). Jackets for oil platforms are redundant structures where even the loss of some members is often within acceptable limits of probability of failure. Lifetime assessments focus on detection of fatigue cracks in combination with fracture mechanics analyses. For offshore wind monopiles, however, Ziegler and Muskulus (2016c) have shown that the probability of detecting decisive fatigue cracks for lifetime extension of monopiles is small as the crack growth is expected to progress fast in the circumferential welds of these structures once it reaches a certain size. The authors conclude that numerical fatigue reassessment and structural monitoring is needed for lifetime extension decisions of monopiles. The state-of-art of lifetime extension in the onshore wind industry is reviewed by Ziegler et al. (submitted). Typically, lifetime extension assessments have an analytical and/ or practical part. The analytical part is a numerical fatigue reassessment where structural loading is recalculated with updated design models and assumptions (mainly environmental and operational conditions) (Ziegler and Muskulus, 2016). The practical part is on-site inspections, which would be possible but expensive due to offshore risks (Ziegler and Muskulus, 2016b).

Ersdal G, & Hörnlund E. 2008. Assessment of offshore structures for life extension. *In ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering.* American Society of Mechanical Engineers.

Comment 4: Include a matrix which shows load case combinations, or a reference to where the setup of the mentioned 'design basis and additional 1700 load cases' can be found.

We plan to implement the following Table in Chapter 3.1:

V_W [m/s]	H_S [m]	T_P [s]	TI [%]	TI reduced [%]	IEC load case
2-4	0.5-1.0	5.0-6.0	15-20	5-6	1.2, 6.4
5-8	0.5-1.5	5.0-6.0	15-17	4-5	1.2, 6.4
9-12	1.0-2.0	6.0-7.0	12-15	3-5	1.2, 6.4
13-16	2.0-3.0	6.5-7.5	10-12	3-4	1.2, 6.4
17-20	2.5-4.0	7.5-8.5	10-11	3-4	1.2, 6.4
21-24	4.0-5.0	8.5-9.5	10-11	3-4	1.2, 6.4
25-28	5.5-6.5	10.0-11.0	10-11	3-4	6.4
29-32	7.0-8.0	11.5-12.5	10-11	3-4	6.4

The load case combinations are presented in groups. Each group contains between 100-300 simulations of 10-minute duration with different random realizations (seeds). All wind directions (0-360°) are simulated in bins of 30° with two set of yaw errors. In addition, various wind-wave misalignments between 0-90° are considered for each wind direction.

Comment 5: How does the technical solution of 'strain measurements at one level' look like? What kind of strain gauges are required, how many and where are they placed? What kind of data do you extract from your simulation model at this level?.

We plan to add this explanation in Chapter 3.3 Discussion:
A feasible solution would be to install electrical resistance strain gauges at the upper part of the transition piece. The use of four axial strain gauges placed in 90° intervals around the circumferential is recommended. The redundancy of this setup enables to compare measurements from opposing strain gauges (compression and tension) to check the level of noise on the data. The sampling rate should be in the range of 20 Hz. The strain data must be calibrated and compensated for temperature. The time series of strain measurements can then be converted into bending stress or bending moments.

We plan to add this explanation in Chapter 3.1 Case study:
Time series of the bending moment around a local axis at a single point of the circumferential of tower (near tower bottom) and monopile (near mudline) were extracted from the simulations. The point of the circumferential would be chosen identical to the location of the strain gauges in a practical application.

Specific comments

Comment 6: The BSH has a requirement that a CMS system has to be installed for at least 1/10 of the offshore wind turbines in a wind farm. Do you think the presented method could be a solution to fulfill such a requirement? Looked at it from a different angle, could an already installed support-structure CMS be used as input to your calculations and by this enable LTE calculations without additional sensor measurements?

The BSH had a requirement of installing a CMS for 1/10 out the foundations in the standard BSH-No. 7005 'Design of offshore wind turbines' from 2007. However, this quantitative statement was removed in the new version of this standard from 2015 ('Minimum requirements concerning the constructive design of offshore structures within the Exclusive Economic Zone (EEZ)'). This new standard only specifies that '[…] parameters, such as shifting, deformation, component stress and frequencies, shall be measured and recorded (monitoring) in the area of the foundation elements at representative offshore wind turbine sites.'
We developed our methodology to be readily applicable to the sensor set ups which are already available in many projects (strain gauges at one level). Alternatively, it is also possible to install the necessary strain gauges in existing wind farms, as no work at submerged parts of the structure is required.

We suggest to not insert the details about the BSH standard into the manuscript since it is too much detail for the scope of the paper. However, we plan to clarify in Chapter 3.3 Discussion and Chapter 4 Conclusion that the necessary sensors are often already existing in many wind farms.

Comment 7: Traditional LTE analyses are for example based on strain gauge measurements for a certain period and statistical weather data. Do you know how many strain gauges need to be placed in traditional LTE measurement campaigns of monopiles? How large is the benefit for your solution, both in terms of reduced sensor costs as well as increased accuracy?

From what we have seen so far, the offshore wind industry has not found a consensus on a suitable, cost-effective way to apply lifetime extension analyses yet. This is mainly due to missing experiences and relevance as not many offshore wind farms are older than 15 years up to now. The main benefit of our proposed solution is that it can work with the sensors that many wind farms already have installed (strain gauges at one level). A study of sensor costs and a comparison of prediction accuracy between different structural monitoring approaches is out of scope of this paper and left for future research.

We plan to add a comparison between our suggested methodology to existing solutions for structural health monitoring in Chapter 3.3 Discussion: Reference is made to Perisic and Tygesen (2014) for a comparison between existing approaches for structural health monitoring and our suggested approach. Perisic and Tygesen (2014) compare Kalman filter based methods and modal expansion for criteria including computational complexity, operation in real time, and structural model complexity. Kalman filter based methods have a low computational complexity, use reduced order FE models and can thus operate in real time. The complexity of structural models and computations for modal based algorithms is high resulting in an operation of near-real time (Perisic and Tygesen, 2014). Once the simulation data basis of the methodology presented here is set up, predictions can be performed with almost no computational effort. This makes it possible to analyse large data sets in retrospect also. Algorithms based on artificial intelligence show similar computational performance. These algorithms, however, need sensors at every location for a training period. Perisic and Tygesen (2014) state that Kalman filter based methods and modal expansion perform similarly in terms of accuracy and sensitivity towards measurement noise. Future work with measurement data is needed to evaluate the sensitivity of the proposed methods to measurement noise.

Comment 8: Please include the description of software programs used in the analysis (currently described in Section 3.1) in this section.

Thanks for the comment. We plan to move this to a new Chapter 2.4 Case study.

Comment 9: SCADA-data are commonly recorded and are available for the lifetime of the asset. By retrofitting the proposed method in existing wind turbines, could historical SCADA data in combination with experience from strain gauge measurements be used for an evaluation of the fatigue damage experienced in the past?

Yes, we see the potential here to link the proposed method to historical SCADA data also. This would require a second step of training a model to predict DELs from input of SCADA.

We plan to add in Chapter 3.3 Discussion:

Many wind farms already have strain gauges installed at one level of the support structure. Alternatively, a retrofit of the necessary strain gauges is possible in existing wind farms, as no work at submerged parts of the structure is required. In case of retrofit, there is the potential to link the suggested extrapolation methodology to historical SCADA data (if recorded) in order to estimate the fatigue damage experienced in the past. This requires an additional model to infer DELs from SCADA and (possibly recorded) environmental conditions. This can be, for instance, a neural network algorithm as suggested by Smolka et al (2014).

Comment 10: It is not clear to the reader which number of neighbors you are ending up with, or which do you evaluate as sufficiently accurate. Figure 1 presents 4 neighbors on each side; Figure 10 presents 1 and 10 neighbors; and Table 1 and Figure 5 presents 1 and 15 neighbors. Please be more consistent on the data sets used and analyses performed to evaluate the sensitivity of the approach to different parameters.

Thanks for the comment. We plan to change Figure 1 and 2 for using 15 neighbors also to be consistent with the results presented later.

Comment 11: Have you evaluated to plot Table 1 as bar graph for better readability and direct comparison of the different approaches?

Thanks for the comment. We plan to transform the Table into a bar graph in the revised manuscript.

Technical corrections

Thanks for the technical corrections! We will implement this.