12th EAWE PhD Seminar on Wind
Energy in Europe
25-27 May 2016
DTU Lyngby, Denmark
Session XXXX Paper XXXXXXX

LIFETIME EXTENSION OF OFFSHORE WIND MONOPILES: ASSESSMENT PROCESS AND RELEVANCE OF FATIGUE CRACK INSPECTION

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ABSTRACT

Lifetime extension soon becomes important when the first larger offshore wind farm reach 20 years of operation. Discussion on the topic has already started in industry and academics, but there are no agreements on assessment procedures and solutions to offshore wind specific challenges yet. This paper introduces the lifetime extension problem, existing guidelines and proposes an approach to decision making. The suggested lifetime extension analysis consists of structural reassessment, prediction of remaining useful lifetimes, and a decision model. The focus is on the relevance of fatigue crack inspections for the lifetime extension decision. Fatigue crack growth is modelled for a monopile-based 5MW offshore wind turbine and related to detection probabilities for visual inspection and non-destructive testing on site. Results indicate low detection probabilities of cracks below water which makes on-site inspections unsuited to determine life extension periods. Numerical fatigue reassessments and structural monitoring are required for this purpose. This paper is an introduction to ongoing research on lifetime extension of offshore wind turbines by the authors.

Keywords: Lifetime extension, offshore wind turbine, fatigue crack, inspection, structural reassessment

1. INTRODUCTION

Today, less than 1 GW of the installed offshore wind capacity is midway through its design lifetime, which is typically 20-25 years [1]. In five years, however, the early generation of large offshore wind farms reaches a mature age (e.g. “Anholt”, “London Array”). For these offshore wind turbines (OWTs), reassessment of the structural health will soon become important in order to optimize maintenance and to decide about lifetime extension of the wind farm.

Lifetime extension is appealing to increase return on investment of existing wind farms. The major challenge is to accurately predict remaining useful lifetimes (RUL) of all OWT components since there is only little experience available in the offshore wind industry today. Additionally, uncertainties in environmental conditions, design models and operational loading make it difficult to predict future behaviour of OWTs. Information from monitoring and inspection is valuable to reduce these uncertainties.

Recently in March 2016, the first standard on lifetime extension of wind turbines was published by DNV GL [2] which is applicable to on- and offshore turbines likewise. Additionally, DNV GL published a service specification for certification of the life extension period [3]. The standard requires an individual inspection of each wind turbine at the end of their design lifetime. This practical part shall be combined with renewed load calculations to account for site-specific conditions and current state of the art (analytical part). According to DNV GL [2], this can be either a “simplified approach” using a generic wind turbine load simulation model, a “detailed approach” with the original design model, or a “probabilistic approach” in which structural reliability analysis is performed. From the lifetime extension standard several questions arise, such as (I) which reassessment approach to choose, (II) what is the benefit of monitoring, (III) how to simplify structural reliability analysis for computational intensive load simulations, and (IV) how to evaluate uncertainties of generic wind turbine simulation models.

There is no industry experience for lifetime extension of offshore wind, but other sectors have dealt with this problem for several decades, e.g. lifetime extension of airplanes, bridges, and offshore petroleum platforms. For example, Ersdal [4] discusses lifetime extension assessment and decision making of offshore oil platforms. For the offshore wind industry, however, other criteria might be decisive as turbines are unmanned structures - this lifts the acceptable risk level. Just as industry experience, also scientific publications addressing lifetime extension of OWTs are still very

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limited. Luengo and Kolios [5] review failure modes and end of life scenarios. Kallehave et al [6] present a brief lifetime recalculation for a monopile support structure only considering the first natural frequency. For an example case using the Walney Offshore Wind Farm, an under-prediction of the first natural frequency of 10% in design results in an 88% longer fatigue lifetime [6].

To the knowledge of the authors, there is no published work on how to structure the decision making process about lifetime extension of offshore wind farms. This paper suggests a three-step method of structural reassessment, prediction of RUL, and a decision model. In practise, all wind turbine components and degradation mechanisms must be considered in the decision making process. The focus of this paper, however, is on fatigue degradation of monopile support structures and its detection through on-site inspections.

2. METHOD FOR LIFETIME EXTENSION ASSESSMENT

2.1 Lifetime extension

OWTs are typically designed and certified for 20 years and must be decommissioned at the end of their service life. Lifetime extension describes the continued operation of the asset beyond the end of their design lifetime (cf. Fig. 1a). Renewal of degraded components and retrofits (performance upgrades, e.g. by software update) are options to make the OWTs fit for lifetime extension if necessary. Alternatively, the wind farm is decommissioned and possibly repowered with a new set of turbines [7]. Although there is only limited industrial experience so far, it is anticipated that the building permit on existing wind farm sites can be extended. Nevertheless, project and turbine certification expire after the design lifetime. Insurance policies or public regulations might require a renewal of the certification for lifetime extension purposes, for which responsible parties are wind turbine operators and wind turbine original equipment manufacturers [2,3].

The lifetime extension decision is challenging due to large uncertainties included. A three-step process to structure the decision making problem is suggested. The goal is to keep the effort low since decision-making investments are profitless if no lifetime extension is possible. Figure 1b presents the suggested procedure with the following steps:

1. Structural reassessment to identify the current health status of the OWT after 20 years of operation.
2. Prediction of RUL to account for future uncertainties such as change of environmental conditions and operational scenarios.
3. Decision model that combines predicted RULs with costs, incomes and decision criteria for different end-of-life options.

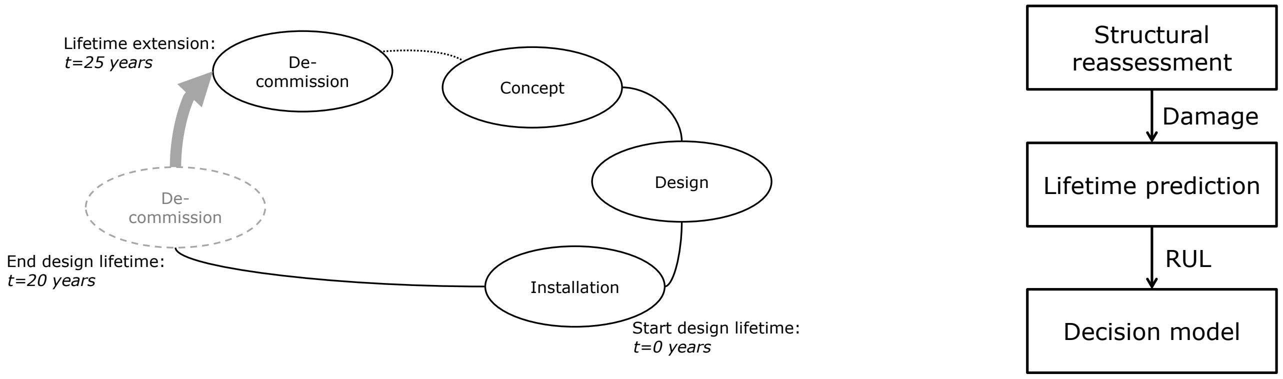

Figure 1. (a) Lifetime extension in the life cycle of OWTs. (b) Required steps for decision on lifetime extension.

2.2 Structural reassessment

The health of offshore wind support structures is affected by material degradation through fatigue, corrosion, scour, marine growth and accidental damages (e.g. ship collision). Structural safety for a specified time is ensured in the design process by evaluating loads and material strengths for several limit states (e.g. ultimate limit state, fatigue limit state, etc.). This design process inherently involves uncertainties; important uncertainties in design and for lifetime extension are presented in Table 1.

Table 1. Uncertain parameters in design and for lifetime extension.

Environmental uncertainty	Soil condition, wind speed, turbulence intensity, wind shear, sea states, water depth, current, marine growth
Operational uncertainty	Time in operations vs. idling, turbine start up and shut down, failures, maintenance, repairs
Model uncertainty	FE models, load models, scour, corrosion, SN-curves

New information on the parameters stated in Table 1 becomes available during the service phase of the wind farm. This knowledge can be used in order to update design assumptions and accordingly decrease the level of uncertainty. Structural reassessment should ideally be a combination of renewed lifetime calculation combined with continuous monitoring, inspection and failure history.

Renewed lifetime calculation describes a rerun of numerical wind turbine models, which simulate loads and structural response, taking into account local conditions and current state of design regulations. If the original design model is not available, DNV GL [2] suggests the use of a generic model for which also an assessment of uncertainty is required. Results are updated fatigue lifetimes of the support structure and other components.

The numerical simulations can be validated with cost-effective *structural monitoring systems*, e.g. measurements of strain or acceleration. It is not possible to monitor every structural hot spot since (a) it would require a large number of sensors (cost restriction), (b) access to structural hot spots can be difficult or not feasible (e.g. under water or seabed), and (c) structural hot spots may not always be known. This makes it necessary to estimate response of the complete structure from only a limited number of sensors [8]. Approaches to identify forces on structures or estimate their response can be model-based (e.g. Kalman filter, joint input-state estimation, modal expansion) or based on artificial intelligence methods (e.g. neural networks). Perisic and Tygesen [8] compared modal expansion and Kalman filter methods for an offshore tripod platform and concluded that both methods perform well. In addition, Kalman filters benefit from low complexity and computational costs. Similarly for offshore wind monopiles, the different model-based approaches yield to comparable results [9]. Kalman filters, however, depend more on additional strain measurements next to acceleration data for operating conditions [9]. All solutions require updating of the finite element model used in design since the as-built structure often has different properties than anticipated. In addition, *continuous monitoring* of environmental parameters (e.g. sea states from wave buoys, wind speed from nacelle anemometer or met-mast) and turbine status (e.g. operation/ parked/ start-up/ shut-down from the SCADA system) is a valuable reassessment input. Other degradation mechanisms, such as scour and corrosion, are typically *monitored periodically* through diver or ROV inspection. For example, loosened bolts, physical and coating damages are inspected yearly and corrosion is assessed bi-yearly in the offshore wind farm “Egmond aan Zee” [10]. On research level, it has been shown that continuous scour monitoring is achievable by natural frequency supervision [11].

Inspections complete the structural reassessment as they verify modelling results and make sure that no gross errors in design, installation, or operation limit the structural integrity. Drawbacks of inspections are: limitation to selected parts of the structure, need to remove marine growth below water, limited probability of detection (PoD), difficult access, and offshore risks for inspection personnel. This makes in-depth inspections very costly.

2.3 Prediction

The damage status of the offshore wind monopile obtained from the previous step of structural reassessment is the basis for prediction of RULs. RUL is a random variable whose bias and variance is determined by the precision and accuracy of the prediction model. These models are either data- or physics-driven. Due to lacking degradation databases for offshore wind monopiles, the physical models used in design and reassessment must be employed. The simplest prognosis model takes the average degradation over the past years and mirrors this to the future. A more defined static prognosis accounts for uncertainties in future environmental and operational scenarios. Advanced trend models capture the evolution of degradation and other parameters over the past and extrapolate these to the future. These models are able to more accurately represent aging mechanisms such as an increase of failure rate towards the end-of-life. Parametrization of the trend models (linear, exponential, higher order), which is restricted by computational efforts of load simulations, is still open for research.

Important trends and uncertainties are: uncertainty in climate and weather phenomena, increase in failure rate and hence turbine idling time, degradation of other turbine components with influence on structural loading, change in wind conditions from commissioning of nearby wind farm. In addition, there are dynamic decision parameters that effect RULs such as retrofits and adaptation of control strategies. A possible adaptation is to reduce loads at the expense of lower power production [12]. This is valuable if the some turbines in the wind farm have less RULs than the rest. Decommissioning of all turbines in the wind park can with thus be aligned to the same date.

2.4 Decision model

RUL predictions are input for the decision model on lifetime extension. Additionally, an economic model is needed to account for costs and revenues for lifetime extension and alternative scenarios. Decommissioning is only postponed by lifetime extension – this can be assumed to have no effect on the decision. In nowadays practice it might be important to consider a decrease in decommissioning costs for postponement due to learning effects in the immature offshore wind decommissioning industry.

A probabilistic decision framework is required since all parameters contain various degrees of uncertainties. Criteria for choosing lifetime extension can be either that the expected gain is positive or that a higher certainty for positive gain is required. The first criterion is suitable for large operators with sufficient number of wind parks, while the latter criterion is more interesting for smaller operators. Optimization methods are useful to decide on the optimal point in time to change from lifetime extension to repowering considering their opportunity costs. Further research is needed on how to integrate adoptable parameters in the decision making process (such as control strategy).

3. RESULTS AND DISCUSSION OF FATIGUE CRACK INSPECTION

A previous numerical analysis of fatigue cracks on offshore wind monopiles has shown that simulated crack growth increased rapidly to the end of the service life [13]. Figure 2 shows the crack growth on a circumferential butt weld of the OC3 monopile for a 5 MW OWT in 20 m water depth. The assessed structural location has a fatigue lifetime of 32.9 years. The service life of the OWT is assumed to be 20 years. Crack propagation due to aero- and hydrodynamic loading was simulated with a linear-elastic fracture mechanics model applying Paris law. The model was calibrated to yield an identical fatigue lifetime as an SN-curve analysis. Further information on the wind turbine model, environmental conditions, and load analysis can be found in [13].

The work of Ziegler et al. [13] was extended here to study the relevance of fatigue crack inspections for the decision on lifetime extension. Inspections and non-destructive testing methods have only limited capabilities to detect fatigue cracks. The probability of correct positive detection of a fatigue crack increases with the crack size. The detection probability for visual inspection and a non-destructive testing method of Alternating Current Field Measurement (ACFM) was implemented as a function of crack growth for the OC3 monopile. The PoD curve was set up with Equation 1 according to the DNV GL recommended practice for fatigue crack inspection planning on offshore structures [14]. In Equation 1 the variable x is the crack length c for visual inspection, but x is the crack depth a for testing with ACFM. The parameters X_0 and b are given in Table 2 for difficult access below water [14]. The crack depth is converted to the crack length according to a semi-elliptical shape with a constant aspect ratio of $a/c = 0.2$ as suggested in DNV GL [14].

Figure 2 shows the PoD of the simulated crack depths over the lifetime of the OC3 monopile. It is assumed that only the result of the single inspection at year 20 is available; inspection outcomes from previous years are not considered. The results for this case study with deterministic crack growth are the following:

- The fatigue analysis results in only a minor fatigue crack at the end of the service life $a_{20years} = 0.51\ mm$.
- The calculated RUL at the end of the service life is 12.9 years.
- The probability of detecting the fatigue crack in year 20 is only 2.3% for visual testing and 32.3% for ACFM.
- The decisive crack depth for a lifetime extension period of 10 years is 0.76 mm for the evaluated hot spot. Cracks deeper than 0.76 mm result in a through-thickness crack in the following 10 years.
- The decisive crack depth is detected with a probability of 3.5% for visual inspections and 40.5% for ACFM.
- If a crack should be detected with a probability larger than 50%, then the remaining service time until failure is 7.6 years for ACFM and 1.1 years for visual inspection.

$$PoD(x) = 1 - \frac{1}{1+\left(\frac{x}{X_0}\right)^{b}} \qquad (1)$$

Table 2. PoD parameters for difficult access under water according to DNV GL [14].

Parameter	ACFM	Visual inspection
x	crack depth a	crack length c
b	0.9	1.079
X_0	1.16	83.03

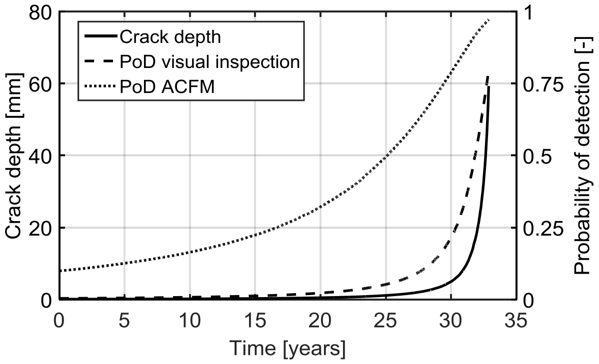

Figure 2. Fatigue crack growth on a circumferential butt weld of an OWT monopile and corresponding probabilities of crack detection for visual inspection and ACFM.

The analysis shows that the PoD of the investigated inspection techniques is very low for decisive crack sizes at the end-of-life. Accordingly, fatigue crack inspections are only useful to verify that no gross errors endanger the structural integrity. However, renewed numerical fatigue simulations and structural monitoring is needed to determine the feasible life extension period. The crack growth is only modelled deterministic here. Future work is necessary to implement a probabilistic analysis and account for updating of crack growth prognoses based on multiple inspections during the service life.

4. CONCLUSION

This paper suggested a methodology for the process to decide about lifetime extension of offshore wind monopiles. Results showed that inspection techniques have a low probability of detection of decisive fatigue crack sizes at the end of the service life for an offshore wind monopile. This indicates that numerical fatigue reassessment and structural monitoring is needed, whose results should be verified by lifetime extension inspections. Further challenges in the assessment and decision making process are (I) integration of unlike wind turbine components and (II) limiting the assessment to a few turbines and extrapolating the results to the complete wind farm. Future research is needed to address these issues.

ACKNOWLEDGEMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 642108.

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