

Subsoil stress reconstruction for fatigue monitoring of offshore wind turbine using accelerometers on the tower

Henkel, Maximilian; Noppe, Nymfa; Weijtjens, Wout; Devriendt, Christof

Published in:

9th European Workshop on Structural Health Monitoring (EWSHM 2018), July 10-13, 2018 in Manchester, UK (EWSHM 2018)

Publication date:

2018

License:

Unspecified

Document Version:

Final published version

[Link to publication](#)

Citation for published version (APA):

Henkel, M., Noppe, N., Weijtjens, W., & Devriendt, C. (2018). Subsoil stress reconstruction for fatigue monitoring of offshore wind turbine using accelerometers on the tower. In *9th European Workshop on Structural Health Monitoring (EWSHM 2018), July 10-13, 2018 in Manchester, UK (EWSHM 2018)* (2018-11 ed., pp. 1-12). NDT.net. <https://www.ndt.net/search/docs.php?id=23396>

Copyright

No part of this publication may be reproduced or transmitted in any form, without the prior written permission of the author(s) or other rights holders to whom publication rights have been transferred, unless permitted by a license attached to the publication (a Creative Commons license or other), or unless exceptions to copyright law apply.

Take down policy

If you believe that this document infringes your copyright or other rights, please contact openaccess@vub.be, with details of the nature of the infringement. We will investigate the claim and if justified, we will take the appropriate steps.

Subsoil stress reconstruction for fatigue monitoring of offshore wind turbine using accelerometers on the tower

Maximilian Henkel, Nymfa Noppe, Wout Weijtjens and Christof Devriendt

Vrije Universiteit Brussel, B-1050 Brussels Belgium

Abstract

Subsoil constraints are seen as a black box. Correct modeling of soil dynamics is still part of research and widely used methods do not necessarily apply to upscaled turbines (e.g. p-y curves [1]). However, direct measurements are not common since expensive and subsoil sensors being difficult to mount and maintain. Still information about subsoil stresses are crucial with fatigue critical welds often found below mudline. This paper presents a combined strategy. Starting from subsoil strain measurements on three operating offshore wind turbines located in the Belgian North Sea much is learned about characteristics of subsoil stresses. Sensor data revealed a high impact of wave load for welds low on the monopile as well as notable contribution of the second order mode on fatigue damage below the mudline. In a second step subsoil stresses are estimated rather than measured. A virtual sensing approach is used to extrapolate measurements from tower accelerometers and one level of strain gauges mounted to the TP to areas close to the seabed. This way stress histories of all fatigue hot spots can be reconstructed, enabling to accurately assess consumed fatigue life. A validation of this concept[2] is already performed for virtual sensors above the water level using accelerometers and strain gauges on the tower. It can be shown that despite uncertainties of dynamic properties a good estimation quality can be achieved for sensors over the entire length of the monopile.

1 Introduction

Offshore wind has favored the monopile foundation for its simplicity in both design and construction. Currently 80.8% of all offshore wind turbines (OWT) use a monopile substructure[3], Figure. 1. This strong presence of the monopile is in strong contrast to earlier consensus in industry. Before 2010 it was not considered feasible to use monopiles beyond 15-20m water depth and for wind turbines with rated outputs above 4MW. However, the most recent projects, e.g. the Rentel wind farm in Belgium, uses XXL monopiles with diameters of 8m to support 7MW wind turbines at 36m water depth.

This gradual increase in diameter of the monopile to XXL size was made possible by continuous improvement of the design codes, improved fabrication and learning from the field. By installing these XXL monopiles, offshore wind energy has ventured far outside the original envelope of offshore engineering knowledge from offshore oil and gas. Resulting uncertainties become apparent with estimation of the soil conditions. Current standards [4] recommend the use of so-called p-y curves (relationship between horizontal pile displacement and bedding resistance) for stiffness definition. However, these curves





Figure 1. The Nobelwind offshore wind farm was inaugurated in May 2017 and uses 3.3MW wind turbines on monopile foundations

are derived from small-scale tests on slender piles under static loading for oil and gas application of the 1960s. While research seeks to improve the estimation quality for offshore wind via calibration on more suitable numerical simulations[1] a noticeable error remains with measurements[5]. As a result large-scale field tests on two sites are conducted by the PISA (Pile Soil Analysis) project in order to improve p-y curves [6] [7]. Given uncertainties also translate into fatigue i.e. gradual deterioration of the substructure over time. To assess the condition of the substructure under ongoing production and for use beyond the design lifetime, one must be aware of the fatigue accumulation in each critical weld. Concerning monitoring strategies, it is not practically nor economically feasible to instrument every fatigue critical weld with a dedicated set-up that allows to measure the stress directly. As an alternative, virtual sensing has been developed for the fatigue assessment of wind turbines on monopile foundations [2]. This technique allows for the estimation of stresses on the monopile using sensors installed on the turbine and transition piece. This contribution focuses on subsoil strain measurements originating from Nobelwind offshore wind farm to learn about deviations between model and the real world. In a second step the applicability of virtual sensing to subsoil welds of the monopile is investigated.

2 Nobelwind measurement campaign

In the Nobelwind offshore wind farm Fig. 1 three monopile foundations were equipped with optical fiber strain gauges, so-called fiber Bragg gratings, over the entire length of the monopile prior to their installation. Currently the Nobelwind windfarm has been operational for several months. While not all sensors have survived the pile-driving, the majority of sensors is functional and recording strain continuously. As such sub-soil strains were recorded during a large variation of different operational and environmental conditions.

2.1 Project motivation

Uncertainties in soil conditions are especially pronounced for small strains. With dynamic loading inducing mainly small strains, the dynamic stiffness is often underestimated lead-

Table 1. Example of the setup for Nobelwind farm at turbines K05 and G10. Sensor placement on the MP varies between the three turbines as site conditions vary.

	height over LAT [<i>m</i>]		sensor type
	K05	G10	
tower	77	77	ACC
	38	38	ACC
	17	17	ACC
transition piece	17	17	SG
	5	5	SG
monopile	-17	-17	FBG
	-28	-31	FBG
	-33	35	FBG
	-35	-38	FBG
	-38	-40	FBG
	-42	-44	FBG

ing to lower loads in the real world and an over-designed substructure [8]. Consequentially resonance frequencies in design are estimated erroneously [9] [10] [11] as observed in the field. Fatigue loading of offshore wind turbines is an interaction of wave loads, wind loads and the first order structural mode of the wind turbine substructure. The design of most offshore wind turbines on monopile is driven by the fatigue life of the welded connections in the monopile [8]. As a result of the design optimization typically the first welds beneath the sea bed are most fatigue critical and determine the lifetime of the offshore wind turbine. If the design is to be further optimized a good prediction of the fatigue life progression in these welds is essential. Subsoil strain data is rarely available and much has to be learned about occurring non-linearities and non-stationary effects. With knowledge about deviations between model and real-world improvement and validation of indirect measurement method virtual sensing[2] is pursued.

2.2 Measurement setup

For the Nobelwind project three turbines were selected in the farm. The three turbines were chosen to reflect the condition of the entire farm. The three turbines included the turbine at the lowest water depth and the deepest turbine in the farm. Also they were chosen at the opposite edges of the farm and one at the corner of the farm. The set of three turbines thus covers the expected range of frequencies as well as wind conditions. All three instrumented turbines received the same basic monitoring concept. The monitoring system sends a measurement file to an onshore server every ten minutes where it is paired with SCADA data. The wind turbine tower was equipped with accelerometers (ACC), strain gauges were mounted at two levels of the transition piece (TP) and on several levels of the monopile (MP). The sensor levels on the monopiles differ between the three turbines to accommodate for differences in the design of the monopiles and different soil conditions. An example of the setup is summarized in Tab. 1 for turbine K05. Resistive strain gauges were chosen for the TP, while fiber Bragg grating strain sensors (FBG) were chosen for the MP.

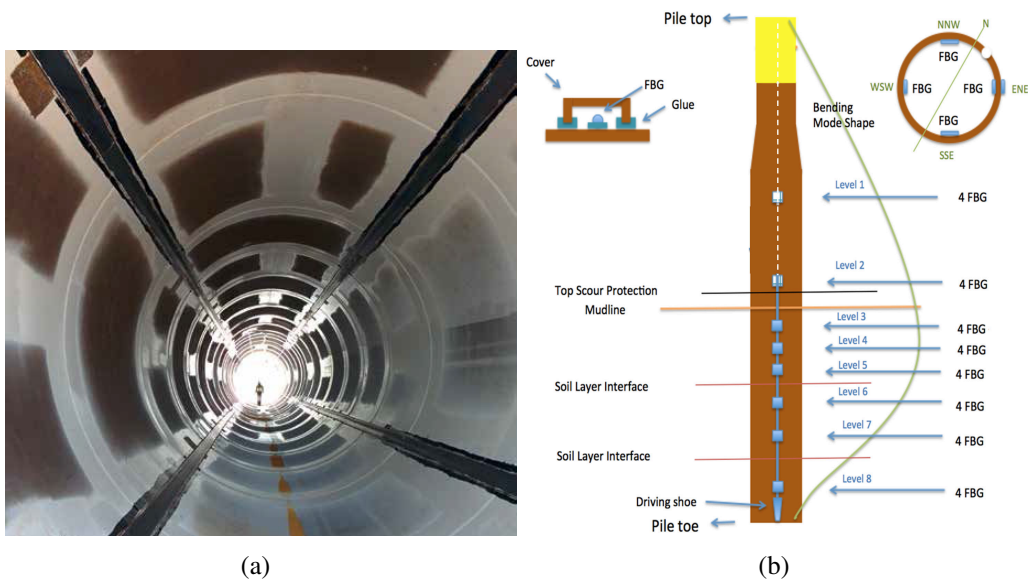


Figure 2. (a) The four optical lines with fiber Bragg gratings inside the MP at the construction yard (b) sensor setup of the MP

2.2.1 Optical Fiber Bragg gratings

All sensors on the monopile had to be installed during the fabrication process of the monopile, as parts of the MP are unreachable once installed. To reduce the installation time and considering the corrosive environment it was opted to use fiber Bragg gratings for measurement of the strain on the monopile. FBG technology allows for sensors at several heights on a single fiber through imprinting of different Bragg gratings into the fiber. The different sensors are identified based on the different wavelengths of the reflected light by the individual gratings.

A total of four fiber lines are glued on the inside of the monopile circumferential distributed as seen in Fig. 2 to allow for the calculation of bending moments using classic bending theory. The vertical position of the FBGs is chosen to accurately capture regions of (assumed) non-linearities. Therefore most sensors are placed around and below the mudline. In addition to the fibers a protective steel cover was glued to the monopile to protect the fibers from the (shear) stresses during pile driving. A driving shoe at the bottom of the steel cover also protects the cover itself. Despite of a number of sensors not surviving the pile-driving, all three monopiles exhibit a sufficient number of sensors in order to perform the desired strain monitoring.

3 Results

This section presents preliminary dynamic analysis of the strain measurements at Nobel-wind farm.

3.1 Dynamic analysis

Screening of strain and acceleration data is done in the frequency domain. The low sensitivity of accelerometers to low frequent oscillation causes the drop in spectral density observed up to 0.15Hz in Fig. 3. As the 10 year mean wind speed at Nobelwind is around 10.2ms^{-1} chosen example matches this wind speed roughly with $v_w = 10.0\text{ms}^{-1}$. In contrast to the accelerometer strain sensors do allow to assess the quasi-static frequency band including the thrust load below 0.10Hz . The rotor induces mainly 1p and 3p oscillation to the dynamics of the structure. The 13.8rpm at rated wind speed translate to the 1p frequency of 0.23Hz as seen in Fig.4. Wave loads range at slightly higher frequencies for calm wind conditions then crossing the 1p frequency for medium wind conditions and ultimately reaching 0.17Hz for strong wind.

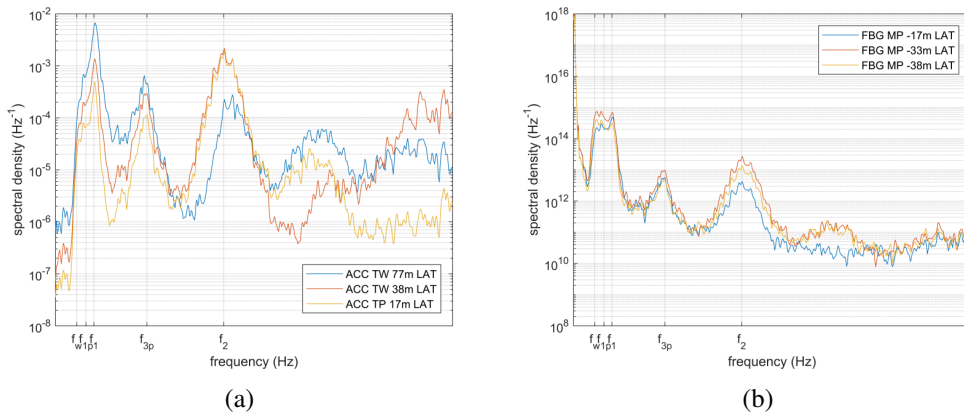


Figure 3. (a) PSD of accelerometers mounted on tower and transition piece (b) PSD of strain gauges of MP at $v_w = 10.0\text{ms}^{-1}$

Above wave frequency the effect of the first structural mode is visible in the spectrum of both accelerometer and strain gauges. With a natural frequency around 0.3Hz the first mode shows an energy decrease for lower accelerometer. In contrast monopile strain data shows increasing spectral intensity for lower sensors pointing towards a load concentra-

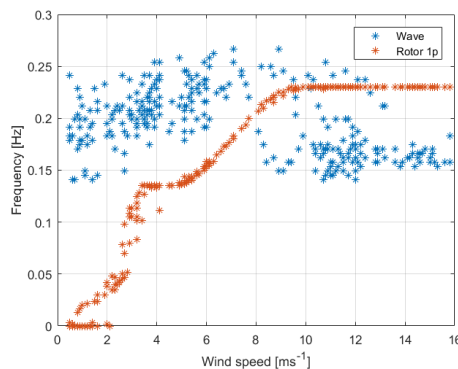


Figure 4. Change of wave frequency and 1p excitation against wind speed for measurement data of two days at turbine K05

tion on the support.

Plotting the spectral intensity only for the above mentioned frequencies of thrust, wave and the first structural mode a relation similar to mode shapes can be established for TP and MP in Fig.5. For this condition with intermediate wind speed the thrust load holds a similar impact on the total dynamic load as wave loading and the first structural mode. While waves being a main dynamic impact for the monopile, nearly no influence is seen at the transition piece. The strain signal is for mean wind speed dominated by wave and first order mode actions. However these contributions are not linearly translated into fatigue damage. Therefore the fatigue consumption over the spectrum is analyzed using accumulation plots Fig. 6. These plots are calculated by filtering the strain data with a varying cutoff frequency, in increments of $0.02Hz$ from $0.02Hz$ to $5.00Hz$. The filtering technique is a sixth order Butterworth low pass filter with connected digital zero-phase filtering helping to preserve features of the unfiltered oscillation. For every filtering instance a linear fatigue damage calculation based on Miner's rule with a S/N curve type D being used for free corrosion $m = 3$, $\log \bar{a} = 11.687$ as defined in DNVGL RP-C203, is performed. Displayed in Fig.6 are load conditions with light wind (a) and intermediate wind (b). For low frequencies fatigue damage is induced by thrust and wave action. All analyzed sensors have their main fatigue gain around $0.3Hz$. However, lower sensors in (a) also hold an increasing importance of higher order dynamics above second mode i.e. 10% on total at the mudline. It should be considered that discussed plots were normalized while total fatigue damage higher on the MP and on the TP is considerably smaller than near mudline. Contrarily to the analysis of the spectrum this preliminary fatigue calculation points out the minor importance of wave and thrust load compared to the first structural mode for structural fatigue.

Given that discussed fatigue accumulation plots are derived from single 10min. datasets their impact is limited. In order to draw a sufficient picture about fatigue consumption around given wind speeds all available 10min. data sets with deviations of $\pm 0.5ms^{-1}$ from v_w are analyzed. Starting from discussed fatigue accumulation plots different fatigue contributors can be distinguished by different slopes in the figure and turning points indicate the change between contributors. In that sense $0.23Hz$ marks the limit of low frequent damage accumulation from wave, thrust and rotor 1p oscillation. Up to $0.4Hz$ solely the first mode acts and is followed by the rotor 3p harmonic until $1.15Hz$. The highest frequent contribution considered originates from the second structural mode and ranges between $1.15Hz$ and $1.5Hz$. Resulting Fig.7 displays the mean relative contribution and standard deviation to fatigue of these mayor contributors. Most fatigue damage is caused by the first structural mode f_1 accountable for at least 60% for light wind or 75% for intermediate wind respectively. However, it is shown that first order mode loses at lower locations while the second order mode f_2 increases influence by 8 to 10% of total fatigue damage. Low frequent contributions f_{lf} are of minor importance for all analyzed conditions contrasting the high PSD values. The 3p rotor harmonic f_{3p} is accountable for up to 15% of total damage for the light wind conditions but drops to the same level as f_{lf} with increasing wind speed. On lower monopile locations generally a higher uncertainty is visible expressed by the increasing standard deviation for contributions especially at higher wind speed. This effect is shaded by the overall higher uncertainty level in terms of damage for lower wind conditions.

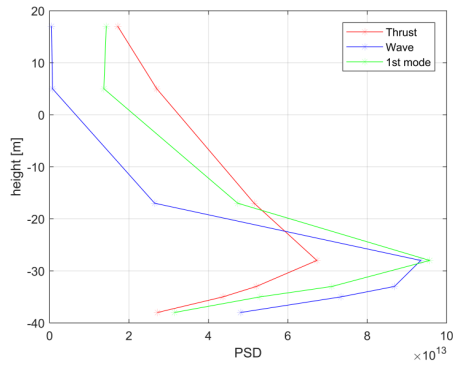
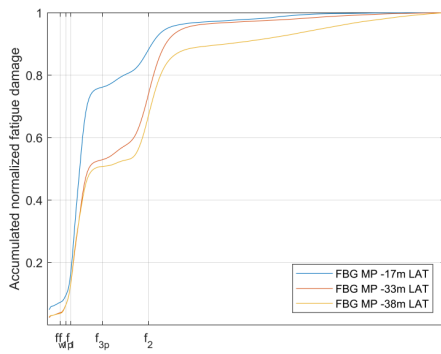
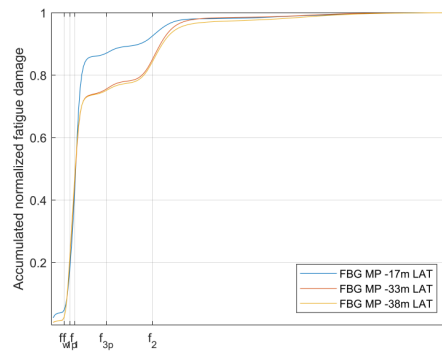


Figure 5. Spectral density of strain sensors on TP and MP split according load at $v_w = 10.0ms^{-1}$

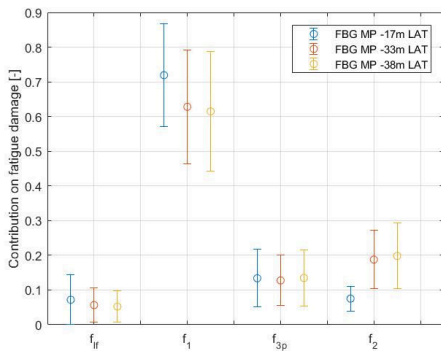


(a) $v_w = 5.0ms^{-1}$

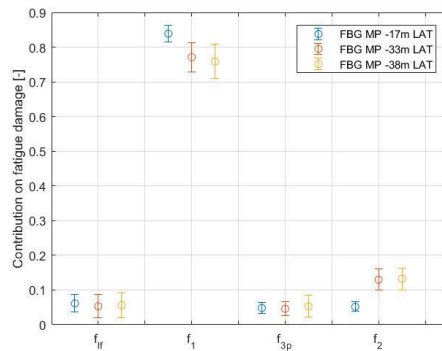


(b) $v_w = 10.0ms^{-1}$

Figure 6. Accumulated fatigue damage of 10min. dataset plotted against the frequency. Different heights on TP and MP are compared for two load conditions.



(a) $v_w = 5.0ms^{-1}$



(b) $v_w = 10.0ms^{-1}$

Figure 7. Fatigue damage split according to contribution for all load conditions with max. deviation of $v_w = + - 0.5ms^{-1}$ from chosen wind speed presented as mean and standard deviation

4 Virtual sensing

Measuring directly at fatigue critical locations i.e. subsoil is rarely seen in offshore wind. On one hand exact location of the fatigue critical weld is difficult to distinguish due to uncertainties in dynamic properties. On the other hand setups have to be installed along with monopile manufacturing bearing the risk of sensor failure while pile driving. As a result stress prediction is favored over direct information and essential for existing wind farms. Virtual sensing incorporates a multitude of different methods with the common goal to predict loads in order to estimate fatigue without the need for a direct measurement.

This contribution focuses on a virtual sensing approach called Modal Decomposition and Expansion (MDE) estimating system response by extrapolating response measurement data coming from a limited set of sensors and the known mode shapes of the structure. MDE assumes the structural dynamics as a linear combination of the structure's mode shape vectors. Based on the modal model vibrations or strains are estimated without required knowledge of the structure's natural frequencies and damping ratios[2],[12, 13][14]. Modal decomposition assumes that the structural response can be expressed as a linear combination of eigenvectors or mode shapes:

$$a_m(t) = \sum_{i=1}^n \phi_{i,m} q_i(t), \quad (1)$$

where $a_m(t) \in \mathbb{R}^{n_m \times 1}$ is a vector that contains the n_m measured accelerations for each time instance t , n is the number of considered modes, $q_i(t) \in \mathbb{R}$ is the modal coordinate component of mode i and $\phi_{i,m} \in \mathbb{R}^{n_m \times 1}$ is the vector with the components of mode shape i at measurement locations m . These mode shapes can be derived either from numerical models or by using operational modal analysis [2]. From Eq. (1), the modal coordinates quantifying the participation of each mode can be identified based on the mode shapes and the measured accelerations. The expression to solve for the modal coordinates is as follows:

$$q(t) = (\Phi_m^T \Phi_m)^{-1} \Phi_m^T a_m(t) = \Phi_m^\dagger a_m(t), \quad (2)$$

where $q(t) = \{q_1(t), q_2(t), \dots, q_n(t)\}^T$ and $\Phi_m = [\phi_{1,m}, \phi_{2,m}, \dots, \phi_{n,m}]$ combines the n considered mode shapes at the n_m measured degrees of freedom (DOFs) and \bullet^\dagger is the pseudo-inverse operator. Note that Eq. (2) can only be solved when the number of measurements n_m equals or exceeds the number of considered modes n . In practical applications this implies that the number of considered modes will be limited by the number of sensors installed on the structure.

The estimated modal coordinates derived from Eq. (2) can be expanded to predict the accelerations and dynamic strains at any point of the structure that is contained in the mode shape vectors obtained from a numerical model. The expansion at such a virtual sensor location p uses the following expression [2]:

$$\varepsilon_p(t) = \Phi_{\varepsilon p} \mathcal{L}^{-1} \left\{ \frac{1}{s^2} \mathcal{L} \{q(t)\} \right\}, \quad (3)$$

where $\Phi_{\varepsilon,p}$ are the mode shapes and strain mode shapes respectively of the n considered modes at the n_p DOFs which correspond to the virtual sensor locations p , $\mathcal{L} \{\bullet\}$ and

$\mathcal{L}^{-1}\{\bullet\}$ are the Laplace transformation and the inverse Laplace transformation, respectively.

In addition, the estimation of strains from acceleration measurements requires the double integration of accelerations to the displacement dimension. This double integration is performed on the estimated modal coordinates in the Laplace domain, resulting in the $1/s^2$ operation shown in Eq. (3).

4.1 Stress reconstruction subsoil

Currently, MDE has only been validated for virtual sensor locations above mudline[2] and still has to be proven for subsoil predictions. In particular the assumptions of a linear model and zero damping might not apply for the subsoil behavior. Locations of virtual sensors are chosen to match FBG sensors of the monopile enabling to benchmark the estimation with real-world sensor data.

In a first step the basic scheme of MDE for estimations above mudline is used. Confidence in the linear modal model is improved by recent research attesting certain soil as linearly behaving for small strains[15]. Eigenvectors are obtained via operational modal analysis[16] to account for site characteristics which would not be covered by a generic FE model. Aiming for the fatigue life at a later stage of this project only dynamics below $3Hz$ are focused on thus only first two structural modes are considered. As discussed in Sec.3.1 the accelerometers in the tower are insufficient to mimic low frequent dynamics. To cover the whole spectrum quasi-statics i.e. all dynamics up to $0.2Hz$ from the top strain gauge of the TP are used as input for virtual sensing along with tower accelerations in the multi-band implementation of MDE [2]. While a better match of the low frequency band is expected for sensors closer to virtual sensor locations, the location at the top of the TP is considered to simulate installation after completion.

Fig.8 presents first results of virtual sensing for light wind. A good agreement between measured (blue dashed) and estimated stress (orange) is achieved for both locations on top of the monopile (a),(b),(c) and below mudline (d),(e),(f). Comparing the shape of the stress curves in time-domain measured and estimated it is found that main loads and their relations are considered sufficiently. Solely amplitude deviations occur for the sensor on top of the MP. Differently, for the subsoil sensor the match of stress curves is worse and amplitude deviations are more pronounced. Translating the problem into frequency domain seen in (c) and (f) a good match for f_1 is achieved accountable for the basic goodness of the stress estimation. Deviations are discovered on one hand for frequencies above thrust load and below first structural mode at $0.10Hz < f < 0.25Hz$. A comparison of FBG on the monopile with the top TP strain gauge used for estimation reveals notable different intensities within given range (not shown). As a result the use of particular sensor to mimic quasi-static behavior can be questioned. On the other hand deviations are visible for frequencies above $0.5Hz$. While the mismatch is significant in the frequency domain further analysis is required to judge the importance for the time-domain signal. In general the subsoil estimation proved to be less accurate with the basic virtual sensing approach however main error sources were common to virtual sensors above and below mudline.

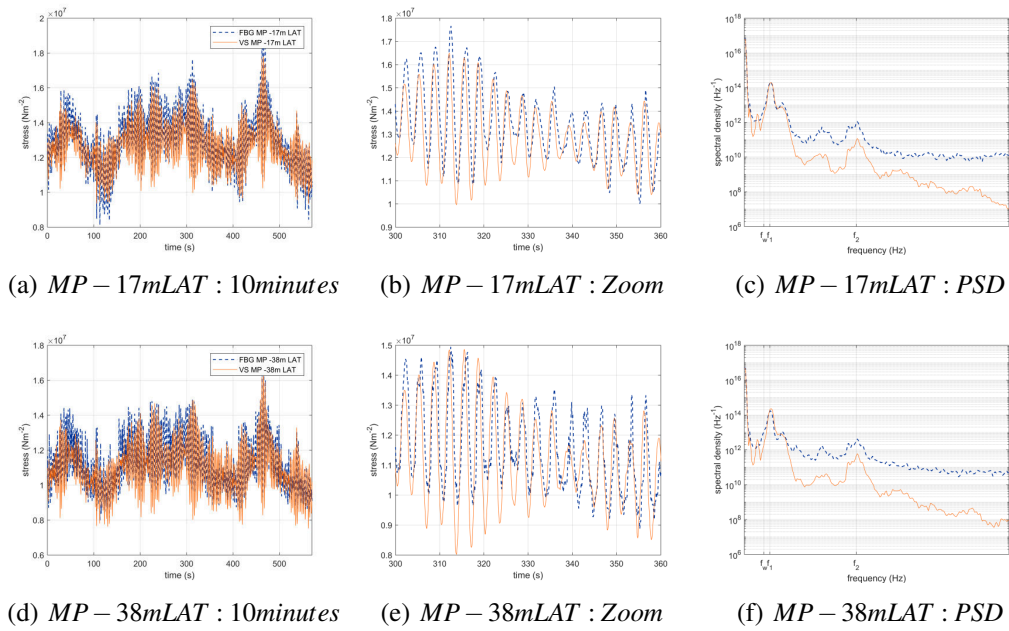


Figure 8. reference load case $v_w=5.6\text{m/s}$ From left to right: Ten-minute time history, detail time history and power spectral density of simulated (blue dashed) and predicted (orange)

5 Conclusions

This contribution discusses first measurement data from the Nobelwind farm in the Belgian North Sea and the first use of virtual sensing subsoil. The addition of sub-soil strain sensors allows to assess statics and dynamics over the entire length of the foundation structure. Spectra of accelerometer on the tower and strain sensors on the monopile draw a picture about fatigue contributions. Furthermore fatigue accumulation illustrates the importance of the second order mode subsoil. Increased scatter in fatigue damage for subsoil locations underlines the need of accurately estimated dynamic properties. In a second step strain data is used in order to benchmark virtual sensing for the use subsoil. While not all influences are captured accurately a good estimation quality is already achieved with a basic model.

In future continuation of this project analysis of the soil conditions will add information about dynamic properties i.e. stiffness and damping which will ultimately allow a full fatigue assessment of the monopile. Additionally, quantification of occurring non-linearities in dynamic properties and variability over time and operational condition is desired. The virtual sensing approach will be expanded and a fatigue analysis will be carried out to benchmark capabilities subsoil.

Acknowledgements

The work shown in this article is part of the O&O Nobelwind with the financial support of the Flemish government and support by Research Foundation Flanders (FWO). The authors gratefully thank the people of Parkwind for their continuous support.

Bibliography

References

- [1] K. Thieken, M. Achmus, and K. Lemke, “A new static p-y approach for piles with arbitrary dimensions in sand,” *geotechnik*, vol. 38, no. 4, pp. 267–288, 2015.
- [2] A. Iliopoulos, W. Weijtjens, D. Van Hemelrijck, and C. Devriendt, “Fatigue assessment of offshore wind turbines on monopile foundations using multi-band modal expansion,” *Wind Energy*, vol. 20, pp. 1463–1479, 2017.
- [3] A. Ho and A. Mbistrova, “The european offshore wind industry: Key trends and statistics 2016,” 2017.
- [4] G. DNV, “Dnv-os-j101–design of offshore wind turbine structures,” *DNV GL*, 2014.
- [5] C. Hübler, J. Häfele, C. G. Gebhardt, and R. Rolfes, “Experimentally supported consideration of operating point dependent soil properties in coupled dynamics of offshore wind turbines,” *Marine Structures*, vol. 57, pp. 18–37, 2018.
- [6] B. Byrne, R. McAdam, H. Burd, G. Houlsby, C. Martin, W. Beuckelaers, L. Zdravkovic, D. Taborda, D. Potts, R. Jardine, *et al.*, “Pisa: new design methods for offshore wind turbine monopiles,” 2017.
- [7] B. Byrne, R. McAdam, H. Burd, G. Houlsby, C. Martin, L. Zdravković, D. Taborda, D. Potts, R. Jardine, M. Sideri, *et al.*, “New design methods for large diameter piles under lateral loading for offshore wind applications,” in *3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, June*, pp. 10–12, 2015.
- [8] F. Vorpahl, H. Schwarze, T. Fischer, M. Seidel, and J. Jonkman, “Offshore wind turbine environment, loads, simulation, and design,” *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 2, pp. 548–570, nov 2012.
- [9] D. Kallehave, B. W. Byrne, C. L. Thilsted, and K. K. Mikkelsen, “Optimization of monopiles for offshore wind turbines,” *Phil. Trans. R. Soc. A*, vol. 373, no. 2035, p. 20140100, 2015.
- [10] P. Doherty and K. Gavin, “Laterally loaded monopile design for offshore wind farms,” *Proceedings of the Institution of Civil Engineers - Energy*, vol. 165, pp. 7–17, 2011.
- [11] S. Bhattacharya, “Challenges in design of foundations for offshore wind turbines,” *Engineering & Technology Reference*, vol. 1, no. 1, 2014.
- [12] A. Skafte, U. T. Tygesen, and R. Brincker, “Expansion of mode shapes and responses on the offshore platform valdemar,” in *Dynamics of Civil Structures, Volume 4*, pp. 35–41, Springer Nature, 2014.

- [13] H. Hjelm, R. Brincker, J. Graugaard-Jensen, and K. Munch, "Determination of stress histories in structures by natural input modal analysis," in *Proceedings of IMAC XXIII, Orlando, FL, USA*, 2005.
- [14] J. Baqersad, C. Niezrecki, and P. Avitabile, "Extracting full-field dynamic strain on a wind turbine rotor subjected to arbitrary excitations using 3d point tracking and a modal expansion technique," *Journal of Sound and Vibration*, vol. 352, pp. 16 – 29, 2015.
- [15] W. Versteijlen, F. Renting, P. van der Valk, J. Bongers, K. van Dalen, and A. Metrikine, "Effective soil-stiffness validation: Shaker excitation of an in-situ monopile foundation," *Soil Dynamics and Earthquake Engineering*, vol. 102, pp. 241–262, 2017.
- [16] C. Devriendt, F. Magalhães, W. Weijtjens, G. De Sitter, Á. Cunha, and P. Guillaume, "Structural health monitoring of offshore wind turbines using automated operational modal analysis," *Structural Health Monitoring*, vol. 13, pp. 644–659, November 2014.