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Sub-soil strain measurements on an operational wind turbine for design validation and fatigue assessment

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Abstract. Measuring on offshore wind turbines is a challenging and cost intensive work especially when aiming for poorly accessible parts of the structure. While it is desirable to replace these measurements by indirect methods uncertainty exists about the necessary assumptions in environmental properties (e.g. soil conditions) and the structural dynamics. This paper presents preliminary results of a measurement campaign of subsoil strains on three operating offshore wind turbines located in the Belgian North Sea. The measurement data enables to check design assumptions e.g. concerns are raised about geometric constraints of the original design. Furthermore the dynamic behavior of the structure is analyzed in order to identify main fatigue contributions. 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.

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[1], 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 [2] recommend the use of so-called p-y curves (relationship between horizontal pile displacement and bedding resistance) for stiffness definition. However, these curves 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[3] a noticeable error remains with measurements[4]. 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 [5] [6]. Differently, the DISSTINCT project calibrates a newly introduced effective stiffness method[7] on dynamic large-scale tests in the Dutch North Sea. In the same sense this contribution focuses





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

on subsoil strain measurements originating from Nobelwind offshore wind farm to learn about deviations between model and the real world.

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 leading 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. Learning from deviations between model and real-world can also help improving and validating indirect measurement methods like virtual sensing[12].

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

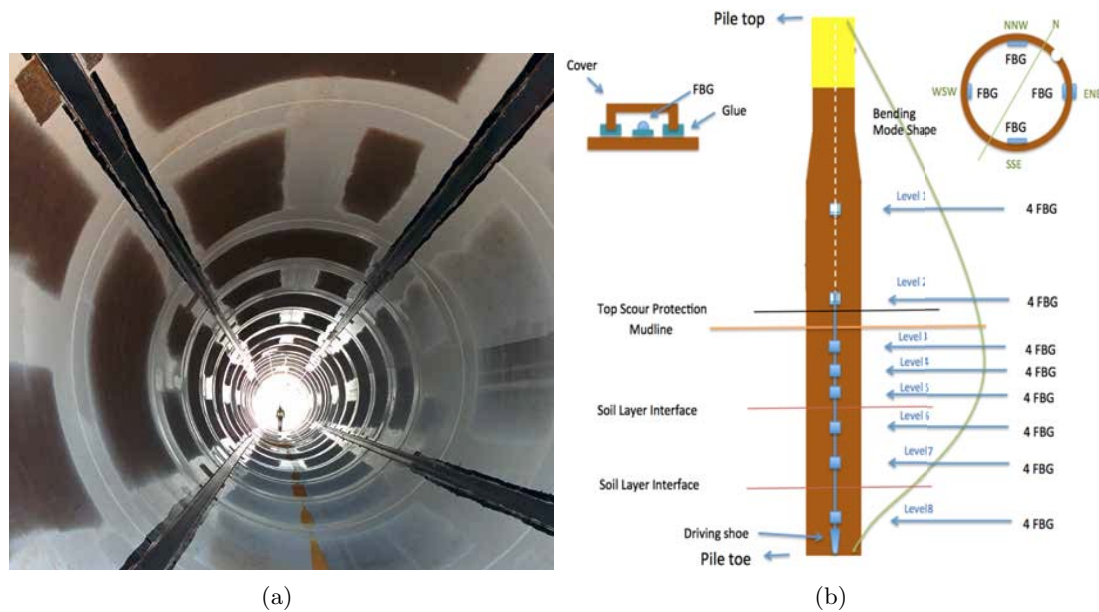


Figure 2. (a) The four optical lines with fiber Bragg gratings inside the MP at the construction yard (b) sensor setup of the MP

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 [m]		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

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.

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

Connected with the Nobelwind measurement campaign are different research interests. On one hand a better knowledge about soil properties is desired playing a vital role for the dynamic response of the structure i.e. determining the resonance frequencies [9, 10]. The development of a more accurate soil model is crucial because designers nowadays still use so called p-y curves derived for oil and gas. These curves do no longer represent the soil behavior of modern day monopiles [10]. An observation backed by the mismatch between design resonance frequencies and in-situ measurements [9, 13].

On the other hand fatigue of subsoil welds commonly drives design lifetime of monopile structures. Assessing the fatigue consumption in order to derive better predictions about remaining useful lifetime is crucial for future turbine designs.

Considering that in the strain data influences of rotor, thrust, wave and wind loading are merged the analysis is split in a quasi-static analysis and a dynamic assessment. The quasi-static analysis focuses on the bending moment and static soil properties while the dynamic part goes deeper into what can be learned for a later fatigue assessment.

3.1. Static analysis

The static analysis aims to improve the linear and time-invariant soil model by inferring soil pressures p and displacements y from the recorded mean bending moments. The approach is similar to the one used in [14] which laid the base of the modern day p-y curves.

In a first step all individual strain gauges were calibrated based on the known SCADA data from each individual turbine. Based on expected bending moments calculated from the SCADA data, in particular wind speed and output power, the offset of the strain gauges is determined over a period of 1 month. This calibration period serves to remove any offsets from installation (both in heading and strain) but does not correct the sensitivity of the sensor. The technique only allows to correct the measured bending moments but not the normal loads. No explicit temperature correction is needed for the sensors below the water level as the temperature around the circumference of the monopile is considered constant and thus would not affect the bending moment. For sensors above the water level individual temperature sensors serve to compensate for any temperature dependency of the strain gauges.

Bending moments are calculated according standard bending theory for hollow cylinders, accounting for the position of the individual sensors and geometry of the monopile. Results in Figure. 3.(a) show the ten-minute mean bending moments for a long period against the wind

speed. Firstly, the typical bending moment curve for wind turbines is visible. The behavior is as expected for the considered pitch-controlled turbine. One can clearly see how the bending moment reduces beyond 11m/s as the turbine reaches rated power and starts to feather the blades. Beyond 24m/s the turbine cuts out and the static bending moment reduces to the unloaded levels.

Figure. 3.(a) also reveals how the bending moment varies for different heights on the turbine. Note that this not imply that the stress levels vary in a same way as the cross sections vary over the length of both the transition piece and the monopile.

Figure. 3.(b) and now plots the normalized bending moment profile against the position on the

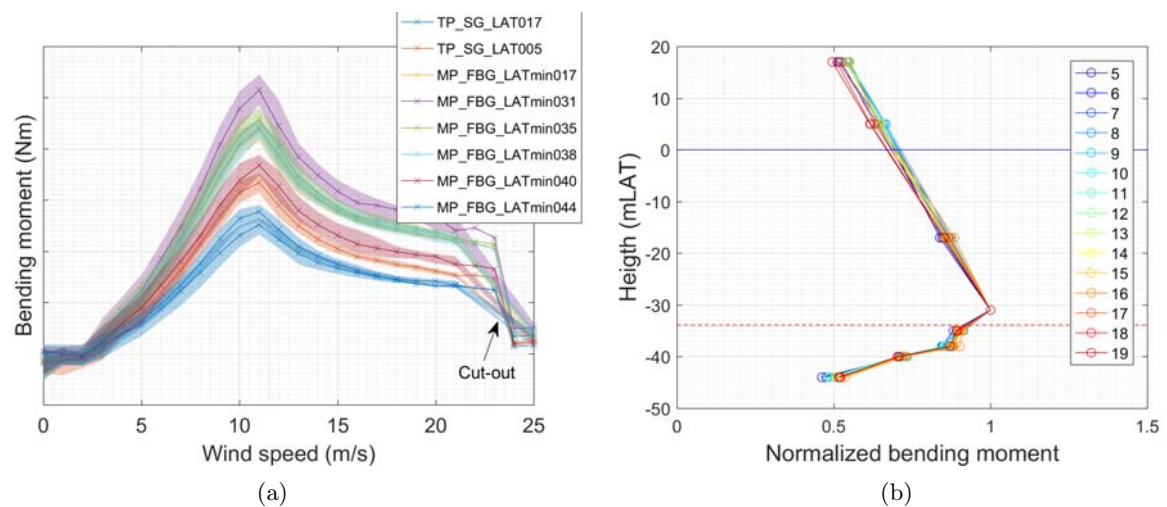


Figure 3. Preliminary results(a) Recorded bending moment plotted against the wind speed, shaded area represent the 10-90th percentile of the measured data (b) normalized bending moment with the depth for different wind speeds. The horizontal blue line indicates the lowest astronomical tidal level (LAT), the red dashed line indicates the design sea-bed level.

wind turbine. The position of the water line (LAT) and the assumed sea-bed level are shown. For the sensors above the mudline one clearly identifies the linearly increasing bending moment induced by the thrust load that acts as a point load on the rotor/hub. The induced bending moments from dynamic loads such as the structural dynamics and the wave loading are not visible as these are averaged out over the 10 minute averaging period.

Below the mudline the bending moments again start to decrease as expected as the load is transferred from the monopile into the seabed. One observation is that the first bending moment just below the mudline is considerably smaller than the last bending moment above the mudline. This is atypical behavior as the bending moment is expected to increase for the first meters sub-soil before decreasing. While the exact cause of this observation is still to be investigated, a potential explanation is that the assumed sea-bed level differs from the actual sea-bed level at the site.

In the near future the results of this assessment will be further processed to identify the soil properties at the site.

3.2. 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. 4. As the 10 year mean wind speed at Nobelwind is around 10.2ms^{-1} chosen

example matches this wind speed roughly with $v_w = 10.0ms^{-1}$. 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.5. 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.

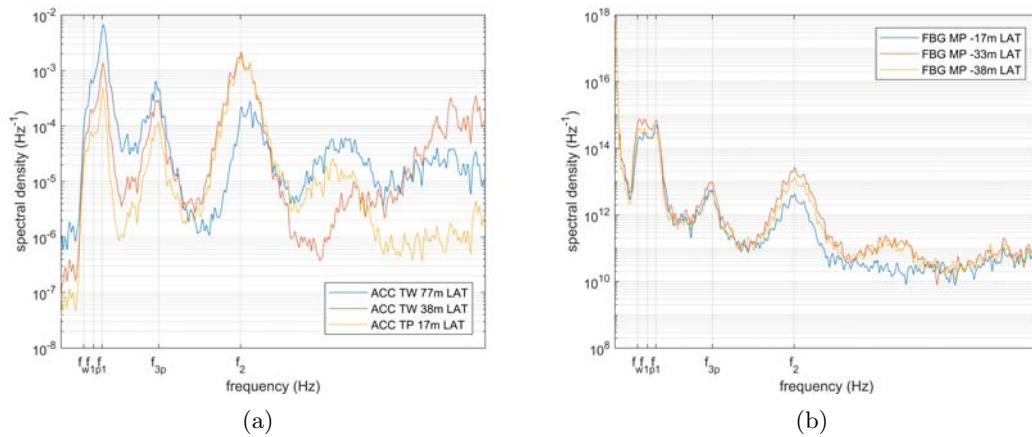


Figure 4. (a) PSD of accelerometers mounted on tower and transition piece (b) PSD of strain gauges of MP at $v_w = 10.0ms^{-1}$

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 concentration 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.6. 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

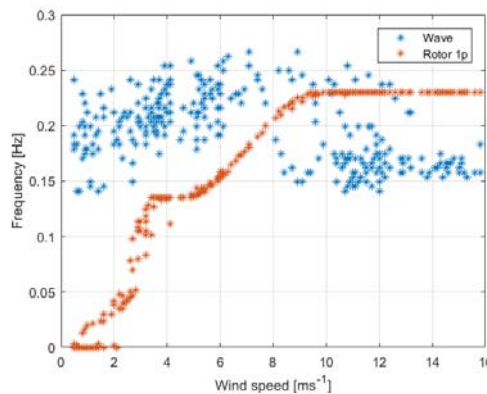


Figure 5. Change of wave frequency and 1p excitation against wind speed for measurement data of two days at turbine K05

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. 7. 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.7 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.8 displays the mean relative contribution and standard deviation to fatigue of these mayor influencer. 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 looses 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.

4. Conclusions

This contribution discusses first measurement data from the Nobelwind farm in the Belgian North Sea. The addition of sub-soil strain sensors allows to asses statics and dynamics over the entire length of the foundation structure. The static analysis helps to understand the strain distribution while 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 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. Within a further step gained information will be used establishing a virtual sensing approach enabling to predict time

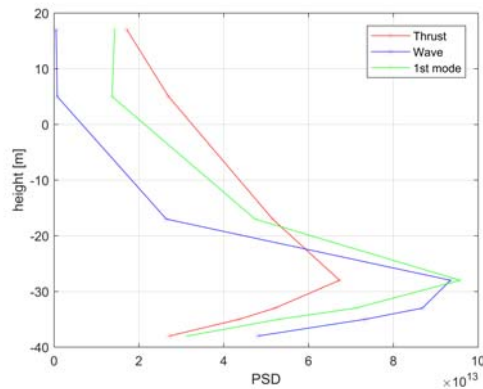


Figure 6. Spectral density of strain sensors on TP and MP split according load at $v_w = 10.0\text{ms}^{-1}$

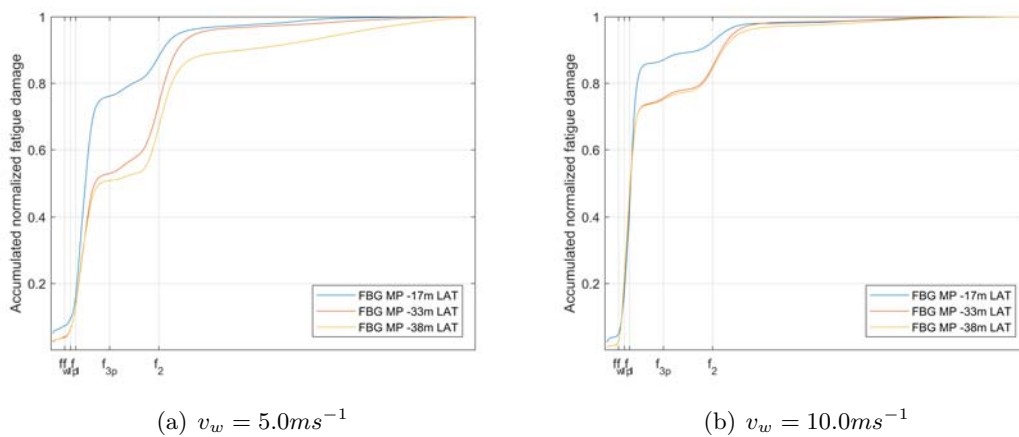


Figure 7. Accumulated fatigue damage of 10min. dataset plotted against the frequency. Different heights on TP and MP are compared for two load conditions.

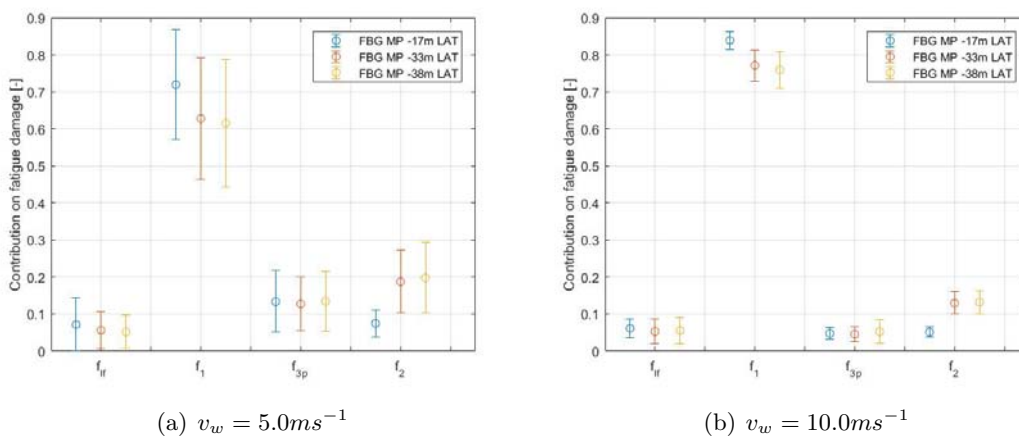


Figure 8. Fatigue damage split according to contribution for all load conditions with max. deviation of $v_w = \pm 0.5\text{ms}^{-1}$ from chosen wind speed presented as mean and standard deviation

variant monopile strain with accelerometers on the tower.

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Bibliography

- [1] Ho A and Mbistrova A 2017 The european offshore wind industry: Key trends and statistics 2016 URL <https://windeurope.org/>
- [2] DNV G 2014 *DNV GL*
- [3] Thieken K, Achmus M and Lemke K 2015 *geotechnik* **38** 267–288
- [4] Hübler C, Häfele J, Gebhardt C G and Rolfes R 2018 *Marine Structures* **57** 18–37
- [5] Byrne B, McAdam R, Burd H, Houlsby G, Martin C, Beuckelaers W, Zdravkovic L, Taborda D, Potts D, Jardine R *et al.* 2017
- [6] Byrne B, McAdam R, Burd H, Houlsby G, Martin C, Zdravković L, Taborda D, Potts D, Jardine R, Sideri M *et al.* 2015 *3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway, June* pp 10–12
- [7] Versteijlen W, Renting F, van der Valk P, Bongers J, van Dalen K and Metrikine A 2017 *Soil Dynamics and Earthquake Engineering* **102** 241–262
- [8] Vorpahl F, Schwarze H, Fischer T, Seidel M and Jonkman J 2012 *Wiley Interdisciplinary Reviews: Energy and Environment* **2** 548–570
- [9] Kallehave D, Byrne B W, Thilsted C L and Mikkelsen K K 2015 *Phil. Trans. R. Soc. A* **373** 20140100
- [10] Doherty P and Gavin K 2011 *Proceedings of the Institution of Civil Engineers - Energy* **165**(1) 7–17
- [11] Bhattacharya S 2014 *Engineering & Technology Reference* **1**
- [12] Iliopoulos A, Weijtjens W, Van Hemelrijck D and Devriendt C 2017 *Wind Energy* **20**(8) 1463–1479
- [13] Tim Verbelen Gert De Sitter C D 2015 *Poster at EWEA Offshore 2015*
- [14] Cox W R, Reese L C, Grubbs B R *et al.* 1974 *Offshore Technology Conference* (Offshore Technology Conference)