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DYNAMIC FIELD DATA FROM OFFSHORE MONOPILE WIND TURBINES – ASSESSMENT OF NATURAL FREQUENCIES AND DAMPING

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Abstract. *The dynamic characteristics of offshore wind turbines are heavily affected by the ambient excitations (e.g. wave excitations and wind excitations) and nonlinear soil behaviour. For monopile structures, the fatigue design for the wind and wave loading is one of the most important problems to consider. Since the fatigue damage is sensitive to the foundation stiffness and damping, increasing the accuracy of analysis tools used in the design and optimization process can improve the reliability of the design and reduce conservatism, thereby leading to a more cost-efficient design. In this context, analysis of field data is important for calibrating and verifying purposes.*

This paper presents analysis of measured accelerations and strains in two offshore wind turbines in the North Sea with monopile foundations. One of the turbines is in a site that is dominated by sand and the other by clay. Field data during idling conditions, collected over long periods of operation, are analysed and the natural frequencies and estimates of damping are determined. Further, the effect of load (wave, wind and dynamic bending moment) on the natural frequencies is investigated and clear correlation between load level and natural frequency is demonstrated, which points to the importance of soil nonlinearity.

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1 INTRODUCTION

According to [1] soil structure interaction (SSI) effects can reduce the fixed-base fundamental frequency more than 15% in the frequency range above > 0.25 Hz. Therefore, analysis tools need to include an accurate description of the soil. In this context, analysis of field data is important for calibrating and verifying purposes. However, only measurements from a few installations are reported in the literature. Some of these are mentioned below.

In [2] analyses of more than 1500 “rotor-stop” tests performed on offshore wind turbines founded on monopiles in four wind parks are described. In [3] analyses of measurement data from one offshore wind turbine structure on a monopile foundation in Horns Reef II wind farm are presented. In [4] results are presented from analyses of 'rotor stop' tests performed on one offshore wind turbine on a monopile in Burbo Banks wind farm. Research in [5] presents results from a load measuring campaign on one offshore wind turbine on a monopile in Horns Rev 1 Wind Farm. Studies carried out in [6] report measurements of overall damping from “rotor-stop” test in the Horns Rev 1 and the Burbo offshore wind farms. Finally, [7] and [8] present data from a long-term monitoring campaign and overspeed stops performed at the Belwind wind farm.

In the present study, analyses of measurement data from two wind farms in the North Sea with monopile foundations are presented. Measured acceleration and strain data collected over several periods of idling conditions are analysed. The objectives of these analyses are twofold. First, to determine the natural frequencies to be used in validation of developed foundation models, and second, to observe any sensitivity of the measured natural frequencies to the intensity of loading, which in turn would point to the role of soil nonlinearity. This paper describes the analyses performed at these sites and the main results.

2 SITE CONDITIONS, TURBINE STRUCTURE AND INSTRUMENTATION

Both sites are located in the North Sea. The ground conditions at the first site are sand-dominated, while the second site is predominantly clay. Measurement data from one tower at each site are used in this study. The tower at the sandy site is equipped with strain gauges at four levels on the inner wall of the monopile (MP) and the inner wall of the transition piece (TP). In this study, measured vertical strain in TP are analysed and in addition, information about wind speed from measurement at the tower is used. The tower at the clayey site is equipped with horizontal and vertical accelerometers close to the tower bottom, and strain gauges at several levels in the tower, the transition piece and the monopile. In this study, measured accelerations in the horizontal X and Y directions and foundation vertical strain are analysed. In addition, information about wind speed and wind direction measured at the tower are used. For both sites, information about significant wave height (Hs) and wave direction are collected from nearby metmasts. For the sandy site, no information about nacelle direction was available from measurements at the tower due to sensor error. The nacelle direction is therefore assumed to be about equal to the wind direction measured at the nearby metmast. Figure 1 shows the monopiles and the location of the instruments. Table 1 gives further information about the sites, the installations and the instrumentation. For the clayey site, for which both strain and accelerometer data are available, the determination of natural frequencies and damping are based on acceleration, since these data have the best quality. For the sandy site, the determination of the natural frequencies and damping are based on measured strain. Assessment of load through dynamic bending moment, is based on measured strain for both sites.

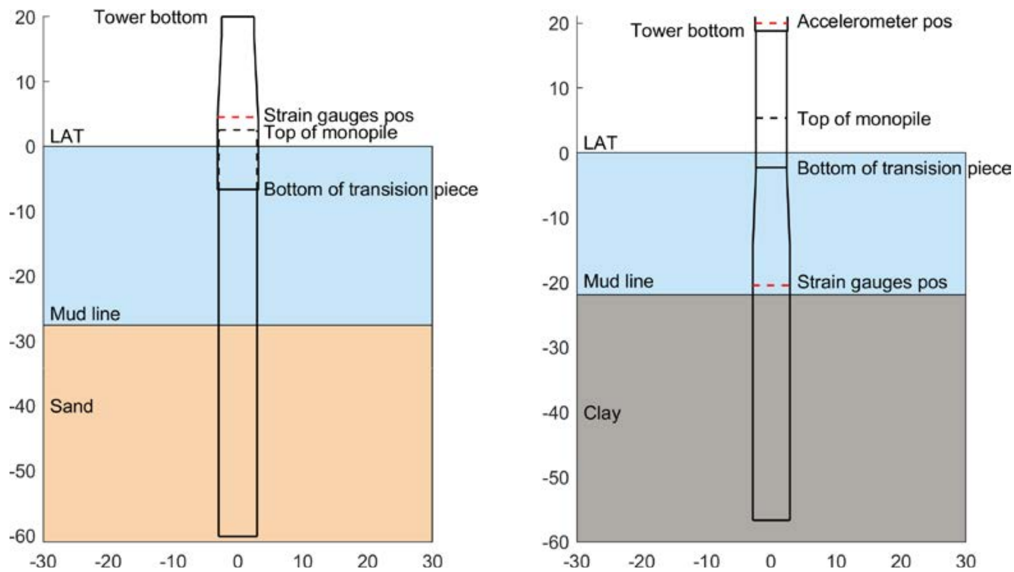

Figure 1: Ground conditions, monopile layout and sensor location, left: sandy site, right: clayey site.

	Site 1	Site 2
Ground conditions	Sand dominated	Clay dominated
Water depth	27 m	22 m
Turbine power	3.6 MW	3.6 MW
Monopile diameter	5.95 m	5.70 m
Instrumentation	4 vertical strain gauges in TP EL +4.5	3 vertical strain gauges in MP EL -20.45. 1 horizontal (X and Y) accelerometer in tower El +20
Sampling frequency	10 Hz	25 Hz

Table 1: Ground conditions, OWT and instrumentation

3 WIND AND WAVE INFORMATION

The response in idling periods are more affected by the foundation stiffness and damping than the response during production, which is primarily influenced by aerodynamic damping and stiffness. Therefore, the focus in this study is on idling periods. For the sandy site, the turbine is idling throughout all time periods from which data were received, while for the clayey site, the turbine is idling in between periods of production. Some of these idling periods lasted only a few minutes, while others lasted for several days. For data used in this study, a requirement is set for a minimum idling period of 24 minutes, with the first and last two minutes discarded to avoid influence from start-up and shut-down of the turbine. Figure 2 shows the distribution of the analysed time periods over wind speeds, wave heights, and wind and wave directions, described as averages in 20-minutes periods. The length of the red bins in the Rose diagrams corresponds to the number of 20-minutes periods with this observation, e.g. about hundred 20-minutes periods with wind direction between 265 and 270 degree for the sandy site.

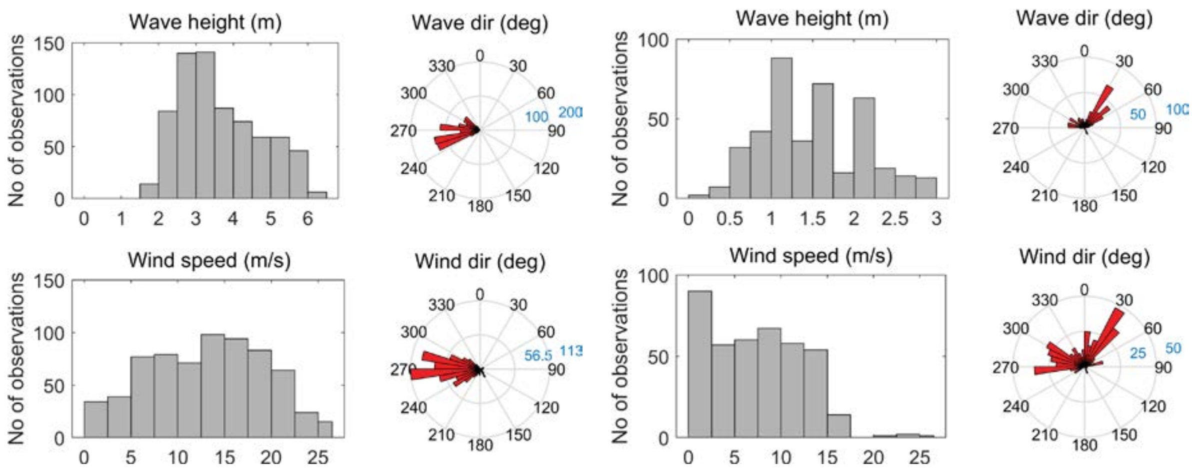

Figure 2: Distribution of average (in 20-minutes periods) wind speed, wave height and wind and wave direction for the analysed time periods, left: sandy site, right: clayey site.

4 DETERMINATION OF NATURAL FREQUENCIES

The natural frequencies are determined using the following FFT based methodology:

- The idling periods are divided into 20-minutes segments and FFT is performed on each segment using a 10-minutes analysis period and 50 % overlap, resulting in one Power Spectrum Density (PSD) for each segment with a frequency resolution of 0.0017 Hz.
- To determine the overall natural frequencies, an average PSD is calculated from all PSDs for the individual time periods, and the natural frequencies are identified from the peaks in the average PSD.
- To study a possible effect of the load on the natural frequencies, the first natural frequencies are determined from the PSDs for all individual 20-min segments and plotted against average wind speed, wave height and calculated dynamic bending moment in the respective 20-min period. Averaging by use of overlaps have the disadvantage of reducing the frequency resolution. Therefore, each determination of the first natural frequency in this part of the study is based on results from FFT analysis of 20-minutes segments without averaging.

The response of an offshore wind turbine is directional dependent due to the thrust on the rotor [3], i.e. there may be a small difference in the natural frequencies in the yaw direction (Fore-aft) and perpendicular to yaw direction (Side-side). Before applying the above methodology, the two directions are therefore analysed separately by transforming the measured accelerations and strains to a local coordinate system determined by the nacelle direction using the following equation:

$$\begin{bmatrix} Side - side \\ Fore - aft \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} \tag{1}$$

where θ is the nacelle direction from North-Y.

Figure 3 shows the overall PSD (average of PSDs from all 20-min periods) with the identified natural frequencies below 2 Hz. The first bending modes can be seen at 0.30 Hz and 0.33 Hz and the second bending modes at 1.70 Hz and 1.59 Hz for the sandy and clayey sites respectively. The peaks in between the 1st and second bending modes are believed to correspond to blade bending modes.

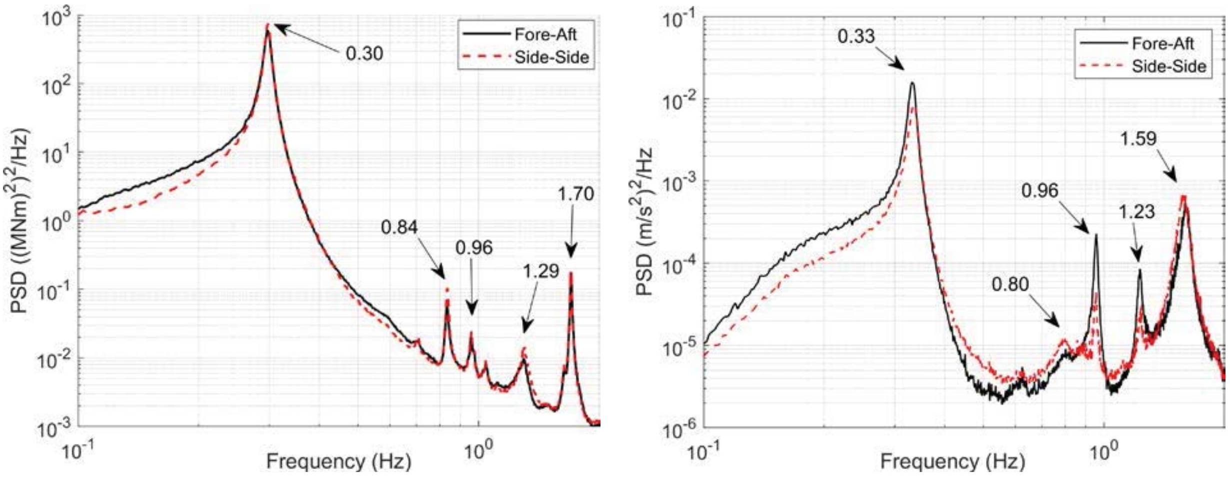

Figure 3: Overall PSD (average of all 20-min periods) with identified natural frequencies below 2 Hz, left: sand dominated site, right: clay dominated site.

Figure 4 shows the first natural frequencies in fore-aft and side-side direction determined for all individual 20-min segments and plotted versus load, i.e. wind speed, significant wave height and total dynamic bending moment (calculated from measured strain) for the two sites. Linear fits to data are also shown in the figures.

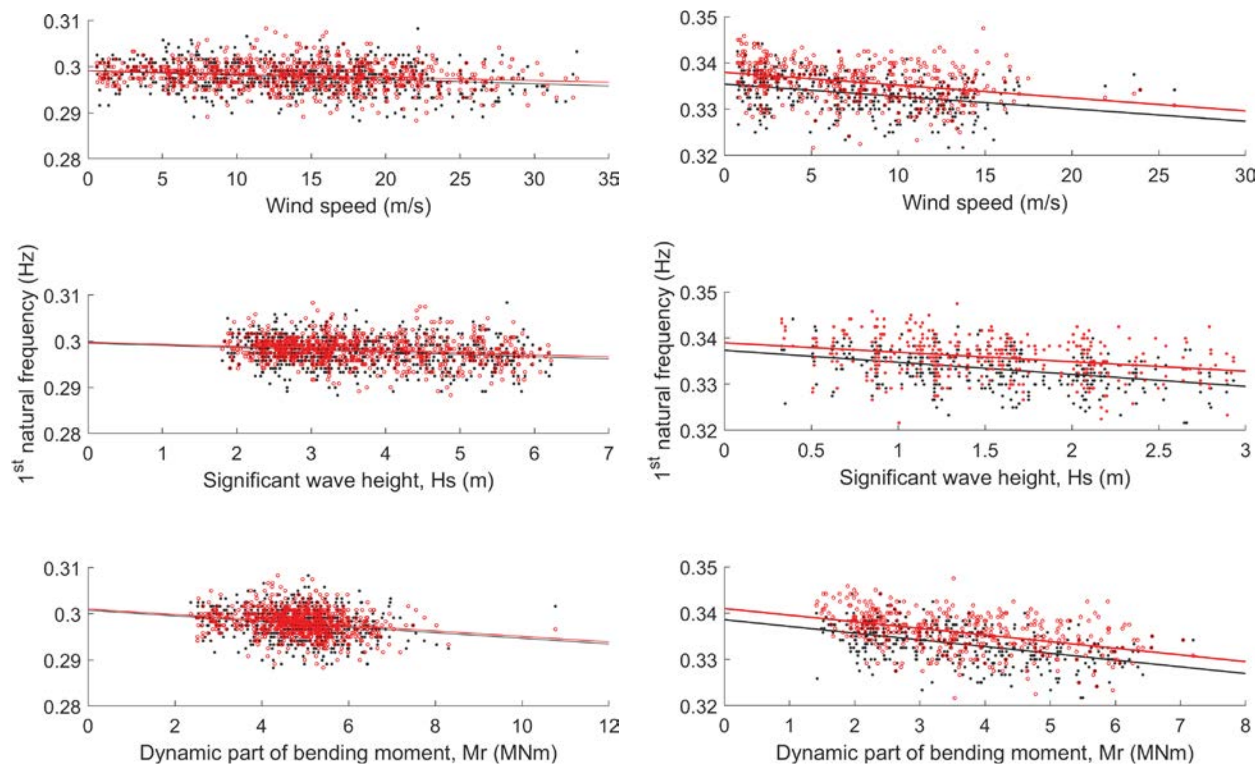

Figure 4: First natural frequency from FFT in side-side direction (red) and fore-aft direction (black) plotted against wind speed, wave height and total dynamic bending moment, left: sandy site, right: clayey site.

The results show that the first natural frequency decreases with increased load, which points to influence of soil nonlinearity. This is most evident for first natural frequency plotted versus the bending moment, which directly represents the load acting on the monopile.

However, Figure 4 also shows quite a large spread in data at the same time as the variation in the natural frequencies with load is very small. To reduce the spread of data and get a clearer trend, it may be considered to increase the frequency resolution by extending the length of the time series used in the FFT. Nevertheless, the wind and wave load are changing with time and the variation in load for each observation will therefore increase if the length of the time series are increased. As an alternative, other methods such as the time domain Multichannel AutoRegressive Moving Average (MARMA) method may be used to yield more accurate spectra with higher resolution compared to FFT. Further, Figure 4 shows that the two modes for the sandy site are not resolved. Methods like MARMA, which are based on analysis of the covariance function and takes advantage of cross information between all channels, will also be much better at identifying closely spaced natural frequencies compared to the FFT method. The MARMA method was successfully tried in the current study and resulted in a clear separation between the two modes and less spread in data compared to FFT.

5 ASSESSMENT OF DAMPING

Damping can be assessed from the measured data both in the frequency domain and in the time domain. Common for all methods is that they estimate the overall damping of the system, which for the first bending modes consists of a combination of aerodynamic damping, damping due to constructive devices, such as a tuned mass dampers, and additional damping, e.g. structural, hydrodynamic and soil damping [8]. When the turbine is parked or idling the aeroelastic damping is very low and it is therefore disregarded in this study.

In the frequency domain, the half-power bandwidth method can be used to estimate the damping ratio. By assuming that the damping ratio ζ is small (less than about 10%), the damping ratio is estimated using the following equation:

$$\zeta \approx \frac{f_2 - f_1}{2f_n} \tag{2}$$

where f_2 and f_1 are the upper and lower half-power frequencies, and f_n is the natural frequency.

For structures with closely spaced modes, possible mode coupling may lead to errors in the damping estimate [9]. For Offshore wind turbine (OWT) structures on monopiles, the first modes in the fore-aft and side-side direction are very closely spaced and a mode coupling is therefore possible. If mode coupling occurs, vibrational energy will be transferred from the highest to the lowest damped mode [2]. Damping determined with the half power bandwidth method should therefore only be considered as estimates of the real damping. Further, to obtain reasonably good estimate of the damping, it is important that the frequency resolution is fine enough for the shapes of the peaks to be correctly represented in the PSD, since a too coarse resolution will make the peaks wider and lower and hence over-estimate the damping. On the other hand, averaging is necessary to obtain peaks smooth enough such that the half power bandwidth method can be applied. In this study the half power bandwidth method is applied to the overall PSD as shown in Figure 3. A single degree of freedom (SDOF) system is fitted to the measured PSD by use of least squares estimation in the frequency range from f_1 to f_2. The damping is thereafter determined from the parameters of the SDOF system. Table 2 tabulates the first natural frequencies and overall damping ratios in fore-aft and side-side direction.

Direction	Sandy site		Clayey site	
	f_n (Hz)	ζ	f_n (Hz)	ζ
Fore-aft	0.298	0.019	0.333	0.021
Side-side	0.298	0.017	0.336	0.025

Table 2: First natural frequencies (f_n) and damping ratio (ζ) determined by the half-power bandwidth method

The measurements at the clayey site show a larger overall damping than at the sandy site. It is assumed that the difference in damping ratio between the two sites is due to the differences in soil properties. However, the tower at the sandy site is equipped with a tuned mass damper, which contributes to the overall damping, while the tower at the clayey site has no damper. Therefore, the real difference in damping between the two sites is probably larger than shown in Table 2. The estimated damping ratios in Table 2 are somewhat lower than reported from rotor stop tests in [4] and [2]. However, in [10] even lower damping ratios was reported from an overspeed test when the tuned mass damper in top of the tower was turned off.

6 CONCLUSIONS

In this study, the first natural frequencies and associated damping are determined from measured dynamic field data from two wind farms in the North Sea with monopile foundations. At the first site, the ground conditions are dominated by sand, and at the second by clay. Only measurement data from periods when the turbines are idling are included in the analyses.

A clear correlation is demonstrated between load level and frequency, which points to the importance of soil nonlinearity. The estimated damping ratio for time periods when the turbine is idling is about 1.7-2.5 %, with higher damping for the clayey site compared to the sandy site. The estimated damping ratios are somewhat lower than reported from other field tests.

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