Subsoil 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 work presents preliminary results of a measurement campaign of subsoil strains on three operating offshore wind turbines located in the Belgian North Sea (figure 1). 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 notable contribution of the second order mode on fatigue damage below the mudline.

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 over-designed substructures [1]. Consequently resonance frequencies in design are estimated erroneously [2] [3] as observed in the field. The design of most offshore wind turbines on monopile is driven by the fatigue life of the welded connections in the monopile [1]. 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 [4].

Measurement setup

Three turbines were chosen for measurements to reflect the range of frequencies and wind conditions of the entire farm:

- Lowest and highest water depth
- 2 on opposite edges and 1 at corner

All three turbines received the same basic monitoring concept. The wind turbine tower was equipped with accelerometers, strain gauges were mounted at two levels of the transition piece (TP) and on several levels of the monopile (MP). Resistive strain gauges were chosen for the TP, while fiber Bragg grating strain sensors (FBG) were chosen for the MP.

Four fiber lines are glued on the inside of the monopile circumferential distributed to allow for the calculation of bending moments using classic Figure 2: MP equipped with bending theory. The vertical position four lines of fiber Bragg of the FBGs is chosen to accurately gratings (upper) and capture regions of (assumed) non-schematic sensor setup linearities. Therefore most sensors are the Nobelwind monopile placed around and below the mudline. (lower)

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Results

Static Analysis: Concerns are raised regarding the mudline assumed in design (red dashed). While the location of maximal bending moment should lie few meters below mudline it is found above posing atypical behavior.

Dynamic Analysis 1: It is illustrated how sensor height influences fatigue damage accumulation in the spectrum. With the seabed being situated around -31 [m] only sub soil sensors show pronounced contribution of the 2nd structural mode.

Dynamic Analysis 2: The dominance of the first structural mode for fatigue damage is shown. Illustrated by mean contribution and corresponding standard deviation also the minor impact of low frequent dynamics i.e. thrust and wave load becomes visible.

Conclusions

The addition of sub-soil strain sensors allows to assess statics and dynamics over the entire length of the foundation structure. Measurements show inconsistencies regarding depth of mudline assumed for the static design of the OWT.

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.

Future work

Analysis of the soil conditions will add information about dynamic properties i.e. stiffness and damping to allow a full fatigue assessment of the monopile. Additionally, quantification of occurring non-linearities in dynamic properties and variability over time and operational condition will be investigated.

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