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Vibration based structural health monitoring of the substructures of five offshore wind turbines

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Abstract

In 2011 a first vibration monitoring system was installed on a single Belgian offshore wind turbine to research the possibility to monitor the structural integrity of the wind turbines substructure using accelerometers. From 2011 to 2017 four more wind turbines have been equipped with a similar setup. A combined total of 15 years of vibration measurements on all five turbines has been collected. In this contribution we will focus how vibration measurements using accelerometers can be used to support operators in decisions on the structural health of their assets.
In the first part of this contribution the vibration behavior of a (offshore) wind turbine will be discussed using measurements obtained from the five monitored turbines. It will be shown how wind conditions, such as wind speed and turbulence, have an effect on the vibration levels of the turbine. In addition the interaction between loads and the tower dynamics will be investigated.
In the second part the focus will be put on the automated operational modal analysis (OMA) that is applied to the measured accelerations. From this automated OMA a large dataset of resonance frequencies and damping values was obtained. The paper will discuss how results from monitoring the resonance frequencies can be used to detect bottom-erosion (i.e. scour) and potentially can be used to monitor the condition of the rotor.

Keywords: Structural Health Monitoring; Offshore wind turbines; Operational modal analysis;

1. Introduction

1.1. Motivation

Offshore wind is developing in Europe at a rapid pace and emerging in the USA and Asia. With growing turbine sizes and greater distances to shore the demand for structural monitoring of the foundations has become more relevant than ever. At present time there are just a limited number of foundation designs in offshore wind. Most used is the so called monopile foundation, in essence a single pile driven into the seabed, which represents over 80% of the total capacity in 2016 [1]. In 2016 alone 88% of the newly installed turbines used monopile foundations, the other 12% of

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installed foundations in 2016 were jacket foundations. Jacket foundations are lattice structures which can be favorable in large water depths and at sites with strong wave action. Other foundation types have been installed in the past but represent a far smaller population, examples are Gravity based (7.5%), tri-pod (3.2%) and tri-pile (1.9%) foundations. Most foundations for offshore wind are designed inspection-free to withstand a given life-time, typically 20 to 30 years, without the need for any inspection or maintenance. The dynamics of the substructure play a vital role in achieving the as-designed life-time. For instance the natural frequency of the first structural mode plays a role in the interaction between waves and the foundation. For instance a design with a lower resonance frequency is more susceptible to wave induced vibrations and thus an increased fatigue load.
Given the role of the resonance frequencies operators are also interested in the boundary conditions of their substructure. In particular the soil conditions play an interesting role, a stiffer soil results in a higher resonance frequency while the development of bottom erosion around the foundation, so-called scour, will reduce the resonance frequency. Modern fatigue-driven designs can have little to no allowance for scour [2], which motivates a monitoring strategy to keep track of scour development. By tracking the resonance frequencies over time the operators gain a direct view on the boundary conditions of their machines and whether the measured resonance frequencies still match the design assumptions. As such many wind turbines are equipped with accelerometers in the nacelle or with a structural health monitoring system consisting of accelerometers on different levels.
The biggest benefit of using accelerometers for monitoring instead of strain gauges is their ease of installation and removal. The installation of strain gauges requires trained personnel, the removal and reapplication of protective paint. In contrast accelerometers can be installed and removed using a magnetic base in a couple of minutes. In addition strain gauges require temperature compensation and calibrations to provide usable results, none of which is necessary for accelerometers. However, accelerometers do not allow to assess quasi-static loads.

1.2. Measurement setup

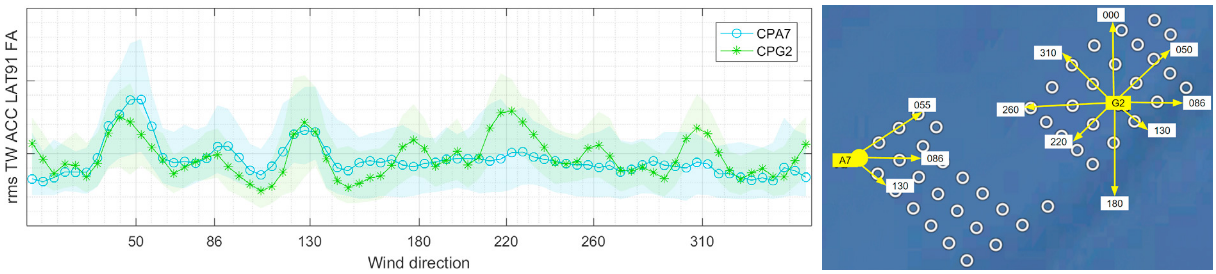
Currently 5 offshore wind turbines outside the Belgian coast, spread over three wind farms Fig. 1, are continuously monitored by OWI-lab. The first turbine at Belwind, a Vestas V90-3MW on a monopile foundation, has been continuously monitored since 2012. The turbine is instrumented with 8 accelerometers, in yellow on Fig. 1.(b), for dynamic analysis. All accelerometers are installed in the horizontal plane, paired in a X-Y configuration. In 2014 optical fiber Bragg gratings (FBGs), in white on Fig. 1.(b), to monitor strain and consequently loads were added. Results from this turbine have been published in several contributions [3–6].
At the more recent Northwind wind farm two turbines, on monopiles, were equipped with an optimized setup in 2014. This research project focused more on load monitoring and has been used to better understand fatigue progression in offshore wind turbines[7].
The final two monitored turbines are located in the C-Power offshore wind farm. The C-Power turbines use jacket foundations rather than the monopile foundations found at Belwind and Northwind.
For the first two instrumented turbines MEMS accelerometers with DC ability were used, for the more recent installations these MEMS sensors were replaced by integrated circuit piezoelectric (ICP) sensors. The ICP sensors provide a better signal to noise ratio than the MEMS but have a lower frequency bound of 0.05Hz.
All accelerometer data is filtered using a 5-th order Butterworth low-pass filter at 5Hz. This was chosen to focus on the lower order structural dynamics, most relevant for fatigue damage. In addition all data is transformed into the nacelle's frame of reference by using the recorded yaw-angle of the wind turbines. As such the Fore-Aft (FA) and Side-to-Side (SS) vibrations are obtained. In [4,5] it was shown that the dynamics in these two orthogonal directions are different. In particular the damping values in the FA direction are far greater than the damping values in the SS direction. This is due to the presence of aerodynamic damping from the airflow over the rotor, which is not present in the SS direction.

2. Dynamic monitoring of offshore wind turbines using accelerometers

In this section we will analyze the vibrations measured at the offshore wind turbines monitored by OWI-lab. In the discussions below the RMS-values of the measured vibrations in either FA or SS directions are used. All results shown are based on several months of measurements.

(a) Overview Belgian Offshore wind farms (b) Belwind (c) Northwind (d) C-Power

Fig. 1. (a) Position of the three monitored wind farms within the Belgian zone for offshore wind energy (b) Belwind V90 turbine (c) Northwind V112 Turbine (d) C-Power Senvion 6MW with indication of accelerometers sensor locations (yellow markers) and strain gauges locations (white markers)



(a) Median RMS vibration levels just below the nacelle vs. wind direction. The shaded area ranges from the 10th to 90th percentile of the RMS vibration levels.

(b) Park lay-out

Fig. 2. The wakes of a wind turbine increases the Fore Aft (FA) vibration levels of the turbine behind it. This is clearly shown in (a) where one observes elevated median vibration levels (line) for wind directions in which the turbine is behind other turbines in the farm, illustrated in (b) for the positions of A7 and G2.

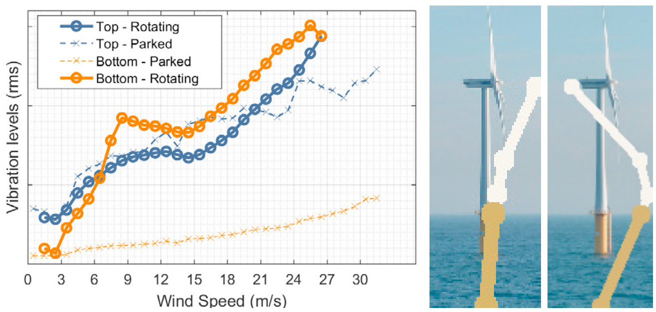
2.1. Wake effects

In this section the role of turbulent air on the vibration levels is analyzed for the C-Power turbines. In Fig. 2.(a) the 10-minute vibration levels of the top sensor are put against the wind direction for rotational speeds larger than 6RPM. G2 has a larger number of wind directions for which the vibration levels have increased. In contrast this only happens at three wind directions for A7. This is due to the fact that A7 is at a corner of the farm and only rarely catches the wake of another turbine. By comparison G2 is positioned in the middle of the farm, thus surrounded by other turbines, and increased vibration levels are visible for each wind direction in which the turbine is directly behind another turbine in the farm. This is illustrated in Fig. 2.(a-b) where the observed vibrations are linked to the actual configuration of the C-Power farm. For the investigated turbine this wake effect can result in up to factor 2 difference between in-wake and outside of wake vibration levels. Earlier results in [7] already confirmed that this reflects in the fatigue loads on the turbine. Using simple accelerometers can thus help to quantify the severity of the wake effect on different turbines in the farm without the need to install strain gauges on all.

2.2. Operating conditions

A wind turbine should not be considered as a static system. It is important to understand that wind turbine dynamics are also related to the operational conditions. The biggest difference lies between operating and parked conditions. In parked conditions the wind turbine is basically a top-heavy slender tower in the sea subjected to wave loads. As the rotor is not rotating the amount of aerodynamic damping is limited. A parked turbine is as such is more susceptible to the wave load exciting the first mode. This can be seen in Fig. 3.(a) where the vibration levels for both the top and bottom accelerometer are provided for a Northwind turbine. The vibration levels observed in parked conditions are not significantly lower than in operating conditions for the top sensor. In contrast for the bottom sensor at the interface level, where the turbine tower is connected to the substructure, there is a clear reduction of the vibration levels once the turbine stops rotating.

Moreover, the results in Fig. 3.(a) show that the vibration levels at the interface actually exceed those at the top level during rotating conditions. This can be understood by considering the mode shapes of the wind turbine in Fig. 3.(b-c). During parked conditions vibrations are dominated by the low damped first mode, located at 0.3Hz, excited by the waves. In operating conditions the first mode becomes heavily damped due to the aerodynamics of the rotor, in addition the higher order modes, with frequencies ranging for different turbines from 1.34 to 1.78Hz, become more excited by the rotor harmonics 3P and 6P. For higher modes the heavy top participate less than the lower levels. As higher modes dominate in rotating conditions this results in the larger vibration levels at the lower levels compared to the top.



(a) Vibration levels versus the wind speed (b) FA1 (c) FA2

Fig. 3. (a) Vibration levels as measured at Northwind for both the top and bottom sensor during rotating and parked conditions. (b-c) Mode shapes of the first and second order structural modes of a wind turbine on a monopile foundation

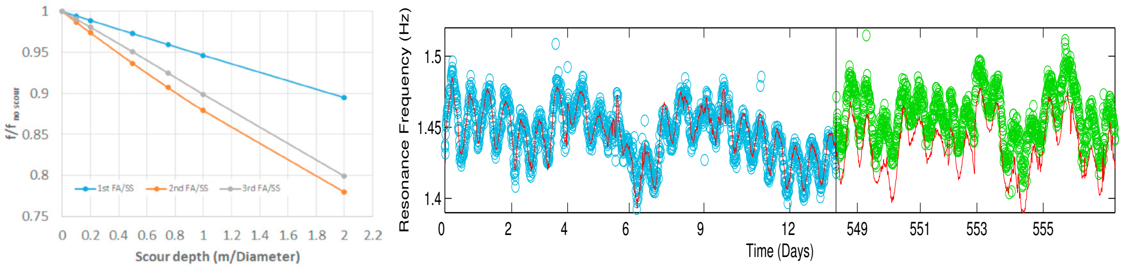
3. Operational modal analysis

Operational modal analysis (OMA) has been already used in structural health monitoring for different civil applications [8,9]. While OMA is not sensitive to small cracks or very local phenomena, operational modal analysis is a strong tool to monitor the boundary conditions of civil structures. Due to the sensitivity of wind turbines to their resonance frequency w.r.t. fatigue life, continuously monitoring the resonance frequency is already of interest to the operators. In addition there still exists an interest in better understanding the damping properties of offshore wind turbines[10]. To answer these requests an automated operational modal analysis tool was developed for monitoring the resonance frequencies of offshore wind turbines [11]. However, the results from operational modal analysis can serve additional purposes.

3.1. Scour monitoring

The possibility of monitoring and assessing the development of scour was discussed in [2]. In [12] a methodology to monitor the resonance frequencies for scour assessment was suggested. The key concept of the proposed approach was not to use the first order resonance frequency, but rather the second order resonance frequency. This is because the second order mode is far more sensitive to the progression of scour than the first mode, as can be seen Fig. 4.(a). This figure shows the results of a simulation of different levels of scour on a wind turbine on a monopile foundation using a tuned model[13]. This result can be explained by considering the mode shapes in Figure. 3.(b-c). For the second order mode the relative amplitudes of the mode shape near the mudline are larger, making it more sensitive to any variation in the soil conditions.

In addition it was proposed in [12] to monitor the modes in SS direction as the absence of aerodynamic damping allows a far more accurate estimate of the resonance frequencies. However, also environmental conditions, a.o. the tidal level, affect the second order resonance frequency. To compensate this a linear regression data normalization strategy was necessary, Fig. 4.(b). While the method is currently still under development the first results at Belwind revealed that the method was able to detect an increase of the resonance frequency Fig. 4.(b). This result points in the opposite direction of scour, and indicates a stiffening of the structure.



(a) Relative sensitivity to scour

(b) Control chart

Fig. 4. (a) The resonance frequency of the second order mode is an interesting parameter to monitor for scour, as it is more sensitive than other modes (b). However, the environmental effects, a.o. tidal level need to be normalized.

3.2. *Blade monitoring*

Another possible application of OMA from accelerometers on the tower is monitoring the condition of the blades. A possible real-life application for wind turbines is the detection of ice on the blades. While the issue of blade icing is less frequent for offshore wind, it is interesting to investigate the potential of OMA to detect blade icing. It was already suggested in [14] to use sensors on blades and the resonance frequencies of the blades to detect ice. While it is the most logical location to monitor the presence of ice using sensors on the blades, it was shown in [15] that it is also possible to use sensors installed on the tower.

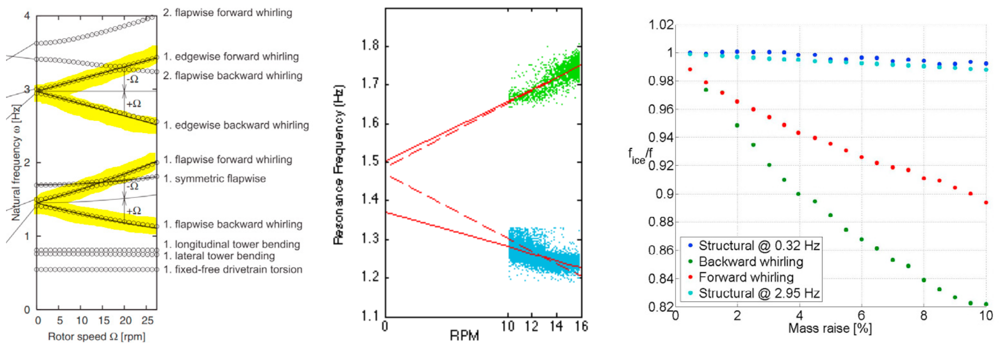
The key lies in using the so-called forward and backward whirling modes. These modes are observed on the tower of a wind turbine, but originate from a rotor mode. The whirling behavior, the modes frequency vary with the RPM, originates from observing a mode in the rotating frame of reference from the fixed frame of reference on the tower [16]. In Fig. 5.(b) the results of tracking these whirling modes on the Belwind wind turbine is shown.

To simulate the presence of ice, the blade mass of the NREL 5MW turbine in simulation software FAST [17] was varied and the tower vibrations at different wind speeds were simulated. Using operational modal analysis different modes of the turbine were tracked. The effect of different levels of ice on the tracked resonance frequencies is shown in Fig. 5.(c). One can see that the first order structural mode is only slightly affected by the build-up of ice. This is because the added mass of the ice is relatively small compared to the total mass of the nacelle and rotor. However, the whirling modes are affected significantly by the ice build up. This is because although observed from the tower, the whirling modes are directly linked to a rotor mode.

In [15] it was concluded that the frequencies of the whirling modes are a possible monitoring feature for blade icing. And while this technique is far from ready for industrial application it proofs the concept to detect blade icing from solely sensors on the tower structure.

4. Conclusions and future work

It was the goal of this paper to motivate the use of accelerometers in a complete monitoring set-up for offshore wind and illustrate their added value. The results from several years of monitoring the vibration levels at offshore wind turbines have revealed the interesting behavior of these dynamic structures. In this paper the wake effect on vibration levels was illustrated, as well as different dynamic behavior during rotating and parked conditions of the offshore wind turbine. The contribution also discussed the posibilities of using operational modal analysis in relevant ways for offshore wind turbines.



(a) Whirling modes [16]

(b) Whirling modes as observed at Belwind

(c) Variation of the frequencies for different levels of ice build-up

Fig. 5. (a-b) The rotor-related whirling modes can be observed from sensors on the tower structure. (c) Whirling modes are more sensitive to ice building up than other structural modes [15]

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