August 27-31, 2023
FLORENCE - ITALY
ICWE 16
16th International Conference on Wind Engineering

Application of structural health monitoring systems for the effective operation of offshore wind turbines

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SUMMARY:
Although the majority of offshore wind farms (OWFs) across the world are equipped with structural health monitoring (SHM) systems, the benefits that could be obtained from SHM are not yet being effectively utilized. This paper makes use of SHM data from operating offshore wind turbines (OWTs) in the North Sea to illustrate some of the benefits that can be obtained from integrating SHM results in the operation and maintenance (O&M) decision-making. The first of the two selected case studies shows the variation of the damage-sensitive eigenfrequency due to maintenance activity at a wind turbine and the second shows the detection of accelerated deterioration of the wind turbine as compared to the others in a wind farm, which initiated further investigation. Furthermore, this paper highlights the importance of integrating the different monitoring systems that exist in wind turbines.

Keywords: renewable energy, offshore wind turbines, structural health monitoring, fatigue damage

1. INTRODUCTION

For a sustainable transition from non-renewable to renewable energy sources being environmentally friendly only is not enough, rather cost reduction and increased reliability of the renewables are very important factors. In the past two decades, technological progress has made significant contributions to cost reduction through innovative designs, the use of enhanced materials and the introduction of more effective construction methodologies. In addition, for the purpose of higher power production, huge wind turbines are being built in more challenging offshore environments. At the very end of 2022, a prototype of the largest wind turbine V236-15.0 MW with a capacity of 15 MW generated its first kWh. Once in full operation, it will be able to generate around 80 GWh per year which can cover the electricity demand for about 20,000 European households (Vestas, 2022). Such a clean energy source can save our planet from around 50,000 tonnes of CO_2 pollution every year, which is equivalent to the annual pollution made by around 10,000 standard passenger cars.

To improve the safety and reliability of wind turbines, SHM systems are installed on the majority of OWFs across the world. Thus, the availability of continuous and reliable information about the status of a wind turbine helps in increasing the system's reliability as damages can be detected at an early stage, resulting in reduced idling time and optimized inspection and maintenance plans through an SHM-based decision-making process. This also helps in reducing O&M costs. As an example: in Germany, until 2015 all OWFs were required to equip 10% of the wind turbines in an OWF with an SHM system (BSH, 2007). In 2015, this requirement was updated giving wind farm operators more flexibility to develop their own monitoring concept (BSH, 2015). However, the majority of the wind farms being constructed nowadays are still following the outdated 10% rule of thumb recommendation. As a result, SHM results are not being effectively utilized as they are usually being done to only fulfil the minimum requirements.

In this paper, two application examples are used to illustrate the added value of SHM for O&M decision-making of operating OWFs in the North Sea. In addition, the importance of a holistic monitoring approach, which combines the information obtained from the different monitoring systems available in wind turbines, is highlighted. The names of the wind farms are not disclosed to maintain commercial confidentiality.

2. METHODOLOGY

In a typical wind turbine (especially offshore), the different sources of information about its status are obtained from SHM, condition monitoring system (CMS), Supervisory Control and Data Acquisition (SCADA) and logbook of the different activities that happened on a wind turbine. SHM mainly deals with monitoring the support structure (blade, tower and foundation), while CMS is devoted to the monitoring of the drivetrain inside the nacelle of a wind turbine and SCADA provides all the environmental and corresponding operational conditions to which a wind turbine is exposed. In this paper, the main source of information is SHM, and the other sources are used to explain the findings from SHM.

SHM systems usually consist of sensors such as accelerometers, inclinometers, displacement transducers, strain gauges etc. (VDI-4551, 2020). The dynamic characteristics of a wind turbine are more reliably obtained from accelerometers and to some extent from all the other sensors. The inclination sensors monitor the permanent deformation of a wind turbine that can be a result of a change in foundation condition or due to grout connection failure (for OWTs with high-strength grout connecting a transition piece with a monopile). Displacement transducers are usually devoted to monitoring a grout connection indirectly through the relative movement between the transition piece and monopile. Strain gauges monitor the stresses that the structure is exposed to during its lifetime, such as fatigue and absolute extreme loads.

For analysis of the SHM data for the considered case studies, the data analysis approach developed in (Tewolde, 2022) is used. The main parameters used here are the first eigenfrequency of a structure estimated by operational modal analysis (OMA). OMA, like for other large-scale civil engineering structures, is used for system identification of wind turbines as it only requires the vibration response time history of a structure as an input, with no need of knowing the excitation forces or boundary conditions. The other parameter is accumulated fatigue damage obtained by postprocessing of the results obtained from rain flow counting according to (ASTM E1049-85, 2017).

3. RESULTS: APPLICATION CASE STUDIES

Two application case studies are considered in the paper. The first shows a change in a wind turbine’s eigenfrequency due to maintenance activity and the second case shows a comparison of the fatigue damage in different wind turbines due to varying operation conditions.

3.1. Change in eigenfrequency due to maintenance activity

The eigenfrequency (EF) of a structure is sensitive to changes in its mass and/or stiffness. Since damage causes a decrease in the stiffness of structures, this makes eigenfrequency a good damage indicator. Thus, a decrease in EF can indicate damage (decrease in stiffness) or/and an increase in dead weight that does not contribute to an increase in stiffness or vice versa.

Fig. 1 shows the first EF of an offshore wind turbine for three days estimated from every 10-minute acceleration raw data. In the continuous monitoring, a sudden increase and decrease of the EF in steps were detected which triggered further investigation. After checking the SCADA and logbook of the wind turbine, it was possible to explain what caused every step of the change. The reason was the removal of some components from the wind turbine to change the main bearing. Usually for exchanging a main bearing, first the gearbox is removed, followed by the rotor and finally the main shaft before changing the main bearing. The components are returned to their positions in the reverse order of their removal. This trend is clearly visible in Fig. 1. Removal of the gearbox resulted in a 15% increase of the first EF, and when the rotor too was removed the EF further increased by 25%. Finally, with the removal of the main shaft the EF reached an increase of about 38%. When the components were returned the same magnitude of EF decrease are observed with the addition of dead weight at every step. Usually, the SHM, CMS, SCADA and logbook are not centralized resulting in unnecessary delays until an anomaly can be explained and a decision made. Therefore, such an example highlights the importance of centralized monitoring system to avoid false alarms. Furthermore, such events can also be used for fine-tuning a wind turbine's FE model.

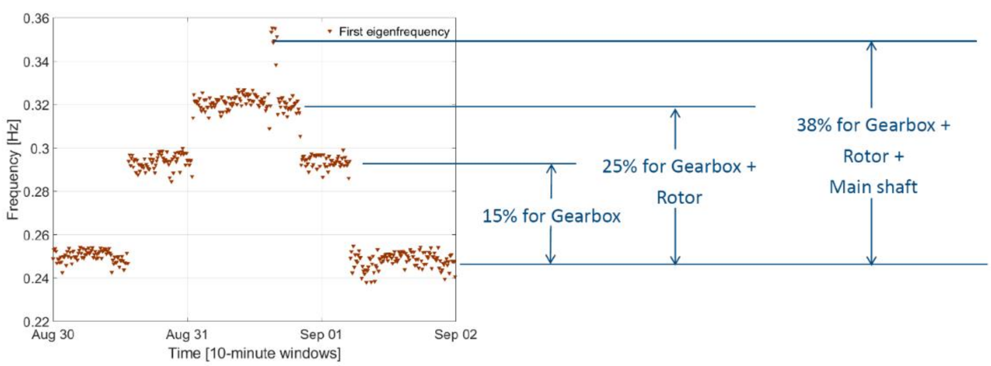

Figure 1. Change in the first eigenfrequency of a wind turbine during main bearing exchange activity.

3.2. Fatigue loads and operation conditions

Usually, the 10% wind turbines equipped with SHM systems in an OWF are selected to represent the variation in design clusters, water depths and geotechnical conditions. However, they are all designed to have similar dynamic behaviour with their first EF in a narrow band. This is achieved by using deeper pile penetration in deeper waters. This results in a similar deterioration behaviour of the wind turbines. Such an opportunity is effectively exploited by designing identical sensor positions for all monitored wind turbines, enabling easier comparisons in real-time to identify the wind turbine not behaving like the majority.

Fig. 2 shows a comparison of the monthly sum fatigue damage at similarly positioned strain gauges from the six monitored wind turbines in an OWF. As expected, all wind turbines showed a similar deterioration trend with higher magnitudes in winter due to the higher wind speed and lower magnitudes in summer due to the lesser wind speeds at that time of the year in the North Sea. An anomaly is observed for turbine number 01 (T01) in the month of April, in which it showed a significantly higher magnitude as compared to the others. After checking the SCADA, it was found that the T01 experienced an unusually higher number of automatic shutdowns and startups in that month. This example also shows the importance of using SCADA data to explain SHM findings so that a decision can be made to inspect the affected wind turbine.

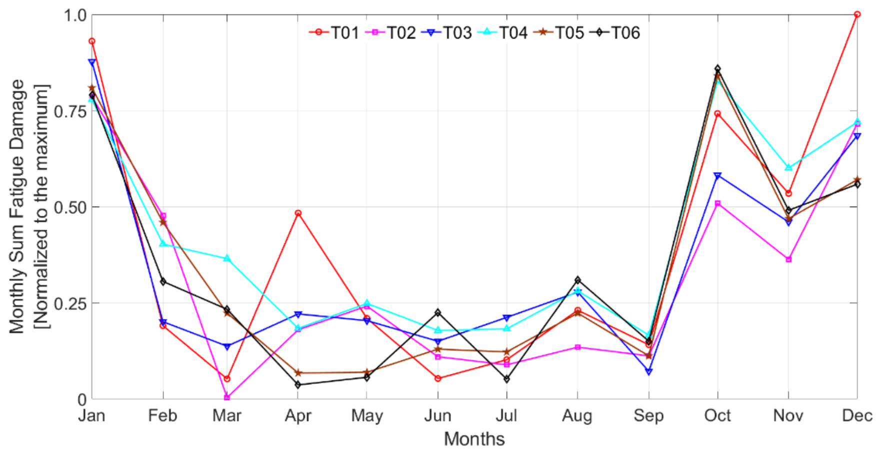

Figure 2. Comparison of monthly sum fatigue damages at similarly positioned strain gauges.

4. CONCLUSION

The paper used SHM data from operating OWTs in the North Sea to show the benefits of integrating SHM results into the O&M decision-making for an effective operation of wind turbines. The selected two case studies used the first EF and fatigue damage parameters calculated from acceleration and strain gauge sensors respectively. The first case study showed how the damage-sensitive EF can also be affected by maintenance activities. And the second case study illustrated the identification of a wind turbine with accelerated deterioration due to a not normal operation condition. Furthermore, in both case studies the importance of integrating the different sources of information about the wind turbine's status is highlighted.

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