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A two-step damage assessment method based on frequency spectrum change in a scaled wind turbine tripod with strain rosettes

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ABSTRACT

The paper presents a proof of concept of a two-step methodology for the damage detection and localization in a scaled model of an offshore support structure. Two damage scenarios have been simulated for validating the methodology. The first damage scenario investigated is deterioration of the support condition which is simulated by removing the attachment of a leg of a tripod to the table and the second scenario is simulated by unbolting the flange to create an artificial circumferential crack in the upper brace of the tripod structure.

The strain measurements have been obtained from a network of Fibre Bragg Grating (FBG) sensors bonded to the model. The damage detection is carried out in the first step using the root mean square deviation (RMSD) estimator. If the RMSD value is above a certain threshold, damage is said to be detected. Experimental results show that additional peaks appear in some frequency regions revealing vibration modes which are associated with damage in the structure. Applying the RMSD estimator to the regions where new peak has emerged it is possible to detect the damage. Once the damage is detected the damage isolation factor (DIF) is used for the damage isolation (level II damage detection). The DIF is based on the RMSD as well, and involves normalization using the rosette set values. Based on the results, it is seen that the DIF shows good localization performance. This good performance can be attributed to the ability of the parameter to overcome biases due to higher relative amplitude of vibration of some rosettes.

1. Introduction

Wind energy appears to be a solution for man's ever increasing energy needs [1]. Wind energy is a green source of energy and an effective measure against global warming and climate change. Through proper design and planning, it may be harnessed as a concentrated and reliable source of energy. Unfortunately, most of the land is occupied by human settlements. Also wind turbines in close proximity of humans have been linked with some adverse effects on human health. Thus offshore wind energy appears to be a better option. It has several advantages such as abundance of wind, stable wind speed and small influence to human beings. Thus, offshore wind energy installations are increasing steadily. Unfortunately, the high cost of energy (COE) as compared to the conventional sources is the major drawback of offshore wind energy. In order to reduce this cost of energy there is an increasing trend to build larger wind turbines in deeper waters.

Offshore wind farms have made significant strides in the last 2 decades since they were commissioned off the Danish coast near Vindeby in 1991. The gravity based foundation was used for this wind farm [2]. But since then, as the wind farms have moved in

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deeper water, novel foundation structures like the jacket, monopile etc. have been employed. For depths of up to 20 m the monopile foundation has been the most commonly used due to its easy design and production as well as the low cost. But it is envisaged that the structural demands at greater water depths ($>20m$) will need more complex foundations like floating or tripod foundations [3,4].

The equation (1) gives the simplified formula for COE [5].

$$COE = \frac{(ICC \times FCR) + O\&M}{E} \tag{1}$$

where, ICC is the Initial Capital Investment costs, FCR is the Annual Fixed Charge Rate, $O\&M$ is the Annual Operation and Maintenance Cost and E is the Annual Energy Production.

As can be seen, in order to decrease the COE, we can decrease the O&M costs and increase the annual energy production.

According to Feng et al. [6], in offshore projects the O&M costs are around 18% of the cost of the project and the offshore wind farms have an availability of only 80% as compared to the onshore wind farms which O&M around 12% and an availability of over 95%. Hence there is a scope for improving the availability of the wind turbines and reducing O&M costs. This can be achieved by the use of Structural Health Monitoring (SHM). SHM allows early detection of damage and allows maintenance planning which reduces the cost [7]. Furthermore, it can allow us to avoid unnecessary downtime hence increasing the availability of the system. Several SHM techniques for wind turbines have been reported in the literature [8–10].

The foundations of offshore structures amount to as much as 25% of the cost of the turbine. Also the foundation is subjected to harsh environments due to uncertain wave loading, corrosion and icing conditions. In addition, there is a high level of uncertainty in the soil-structure interaction. As a result there is a need to monitor the foundation structure. The main modes of failure of the foundation are crack formation due to fatigue and deterioration of the attachment to the sea bed. Fatigue problems in offshore structures have been studied in detail and continue to be an area of interest as reported in Refs. [11–13]. Most of these methods are focussed on localized monitoring of strain. This approach is valid when the hot spots are apriori known. This might not be true in all cases and more global methods are required. The deterioration of the support conditions are structure specific and largely depend on the soil-structure interaction. Most of the work in this area has been based on numerical and computational approaches. For instance Zaaijer et al. made a stiffness matrix of the mud under water to simply simulate the leg restraints of supporting structure of stationary offshore wind turbine [14]. On the other hand Park et al. made dynamic response analysis of an offshore platform which was subjected to seismic movements [15]. They established a three dimensional numerical model of the platform and analyzed the bearing capacity of the legs at the pipe-soil contact under seismic wave [16].

The direct consequence of scouring is the deterioration of the support condition and may lead to failure of the foundation and even collapse of the structure. In order to improve our understanding of the phenomena, a closer monitoring of this interaction is necessary. Thus, in order to fulfill both the goals of damage detection and detection of deterioration of the support condition, there is a need of a global damage detection method. This need of a global method forms the main motivation of this research.

The vibration-based SHM techniques offer a low cost solution suitable for continuous monitoring and hence, are extensively used. The vibration parameters like the frequencies, damping ratio, mode shapes etc. are sensitive to the condition of the structure as well as the boundary conditions and by monitoring their changes, we can monitor the condition of the structure. The theory of processing the vibration data in the frequency domain has been well established. The experimental modal analysis (EMA) or Operational Modal Analysis (OMA) procedures are employed for this purpose [17–20]. The EMA uses the frequency spectrum of the output as well as the input, while OMA is based on output-only. OMA is more suitable for in-situ application as it is not always possible to measure the excitation to the structure in-service.

The OMA has traditionally been employed on acceleration measurements [19–21] but the theory has since then been extended for strain measurements [22,23]. Fiber Bragg Grating (FBG) strain sensors, offer an excellent non-intrusive way for monitoring the structure and hence have been extensively used. The FBG sensors have small size and weight, allow multiplexing which limits the efforts of cabling the structure and have high corrosion resistance [24] which makes them ideal for use in harsh environments. Due to their low weight and capability to perform underwater measurements, they have been employed in the current work.

The paper proposes a two-step method for damage detection and support condition deterioration of tripod structures. At the first step, damage is detected using the root mean square difference (RMSD) of the frequency spectrum of FBG strain sensors. If the RMSD value exceeds a certain threshold, the damage is said to be detected. The threshold is determined based on trade off between false positive and false negative detection. Once the damage is detected, for the isolation of the damage a novel metric named the damage isolation factor (DIF) has been proposed. The DIF too is based on the RMSD but at the rosettes level which also makes use of the symmetry of the structure. Again in order to determine the exact location of damage, and to determine the presence of multiple damage sites, a threshold value is used. The component of the structure is damaged if the DIF value for that rosette exceeds the threshold value.

The novelty of the paper is the two step methodology. In addition the threshold value based on the probability of detection has been obtained through the use of statistical tools. The paper shows the successful implementation of the methodology for detecting a crack in the structure as well as for detecting deterioration of the boundary conditions. The proposed methodology is employed on experimental data from a scaled model of a tripod structure. The paper is the extension of the work of the authors reported in Ref. [25].

The paper is organized as follows. Section 2 presents the tripod geometry, strain sensing network, and the experiments performed. In Section 3 the methodology used for condition monitoring is explained. The Section 4 presents the numerical model and the validation which has been used for drawing conclusions. The results of damage detection as well as selection of the threshold values are presented in Section 5. Based on the results obtained in section 5, some conclusions are provided at the end of the paper and the