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A modal decomposition and expansion approach for prediction of dynamic responses on a monopile offshore wind turbine using a limited number of vibration sensors

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ABSTRACT

Structural health monitoring of wind turbines is usually performed by collecting real-time operating data on a limited number of accessible locations using traditional sensors such as accelerometers and strain-gauges. When dealing with offshore wind turbines (OWT) though, most of the fatigue sensitive spots are inaccessible for direct measurements, e.g. at the mudline below the water level. Response estimation techniques can then be used to estimate the response at unmeasured locations from a limited set of response measurements and a Finite Element Model. In this paper the method will be validated using accelerations only. The method makes use of a modal decomposition and expansion algorithm that allows for successful response prediction. The algorithm is first validated using simulated datasets provided from HAWC2 and then using real time data obtained from a monitoring campaign on an offshore Vestas V90 3 MW wind turbine on a monopile foundation in the Belgian North Sea.

1. Introduction

Online monitoring of wind turbines is a more and more critical issue as the machines are growing in size and offshore installations are becoming more common. To increase power generation and limit the weight, the turbines are becoming structurally more flexible, thus an accurate prediction of their dynamic behavior is mandatory.

Offshore wind turbines are exposed to a variety of dynamic loading scenarios for which fatigue accumulation needs to be monitored and tracked over the course of the life of the structure [1]. Generally, the loadings are of a level and occurrence to be considered normal routine loads and the design of the structure is built to accommodate these conditions [2]. Several contemporary aeroelastic simulation tools coupled with structural dynamics models enable designers to detect, understand and solve most of the possible problems at early stages and optimize their designs [3–12]. However, there are often other environmental and operational conditions (EOC) which are more severe and more important to the overall load and fatigue accumulation for the structure. Considering the fact that the complicated interactions among different parts of the structure

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are represented better through real response measurements, several tests in laboratory scale have been conducted as an attempt to assess the integrity and the dynamic behavior of the structure [13–17]. In all the aforementioned surveys, the excitation is exactly known or/and the responses can be measured in a sufficient large number of points.

Unlike small scale applications, in the case of full scale monopile offshore wind turbines, fatigue sensitive spots are located in sections where mounting sensors are impossible or practically unfeasible (e.g. the muddline 30 m below the water level). Thus, an important issue when performing continuous monitoring of an offshore wind turbine is the limited availability of operational measurement data due to the limited set of physical sensors distributed over the turbine components. The limited sets of sensors (accelerometers and strain gauges) are insufficient to accurately depict the true stress–strain imposed on the structure. In order to assess the actual dynamic behavior and response of the structure, more sophisticated utilization of the limited data available needs to be performed. The issue of limited information due to limited availability of operational data is overcome by using an updated and properly calibrated finite element model. The calibration is performed by comparing the experimentally obtained mode shapes with the corresponding numerical mode shapes in terms of the Modal Assurance Criteria (MAC) [18,19]. As long as the finite element model is calibrated, the combined use of operational acceleration data and mode shape components derived from the finite element model is able to provide sufficient information for the prediction of accelerations at different levels along the height of the structure [20]. The prediction is based upon a modal decomposition of the measured accelerations that results in the estimation of the modal coordinates [21]. The relation between the modal coordinate and the acceleration in an arbitrary point is established by making use of the numerically obtained mode shapes [21]. This paper will demonstrate and validate the proposed approach for the continuous monitoring of the vibration levels of offshore wind turbines using both virtual and real data. First, different virtual wind-wave loading conditions with their resulting responses of the wind turbine, obtained from the fully coupled hydro-aero-servo-elastic simulation tool HAWC2, will be used for validation. Then, different real-time operating cases of the wind turbine will be examined, such as rotating, parked or idling conditions as well as an overspeed test of the rotor. All experimental data has been obtained during a long-term monitoring campaign on an offshore wind turbine in the Belgian North Sea. State-of-the art operational modal analysis techniques and the use of appropriate vibration measurement equipment allowed obtaining high quality acceleration data and accurate estimates of the natural frequencies, damping ratios and mode shapes. The paper is structured as follows. First, the necessary theory followed by the main features of the tested turbine and utilized measurement systems are described. Then the identified modal parameters using state of the art Operational Modal Analysis (OMA) are presented. Next, the finite element model is described. It will be shown that the finite element model is in good agreement with the experimental model in terms of modal characteristics. Finally, the response prediction theory will be both validated by HAWC2 simulations and using the real measurements.

2. Theory

2.1. Modal decomposition

If we consider a model of a structure with no damping, the equation of motion of the structure subjected to a force $f(t)$ is given by

$$M\boldsymbol{a}(t)+K\boldsymbol{x}(t)=\boldsymbol{f}(t) \tag{1}$$

The eigenvalue equation is then expressed as follows:

$$M\boldsymbol{\varphi_i}\omega_i^2=K\boldsymbol{\varphi_i} \tag{2}$$

where M is the mass matrix, K is the stiffness matrix, ω_i is the eigenvalues, $\boldsymbol{\varphi_i}$ is the mode shape vectors and $\boldsymbol{a}(t)$, $\boldsymbol{x}(t)$, $\boldsymbol{f}(t)$ are the acceleration, displacement and force vectors respectively.

By making use of the modal decomposition approach [22–24], the displacement vector can be written as a linear combination of the mode shape vectors

$$\boldsymbol{x}(t)=\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}}\boldsymbol{\varphi_i}q_i(t) \tag{3}$$

or in matrix form as follows:

$$\begin{aligned}&\boldsymbol{x}(t)=\Phi\boldsymbol{q}(t)\\&\Phi=[\boldsymbol{\varphi}_1\quad\boldsymbol{\varphi}_2\quad\dots\quad\boldsymbol{\varphi_n}]\\&\boldsymbol{q}(t)=[q_1(t)\quad q_2(t)\quad\dots\quad q_n(t)]^T\end{aligned} \tag{4}$$

where $\boldsymbol{q}(t)$ is the vector of the displacement modal coordinates for each time instance t, Φ is the mode shape matrix, n is the total number of modes and $[.]^T$ denotes the transpose of a matrix. For most practical problems though, it is not necessary to use all mode shapes, since a good approximate solution can be obtained via modal superposition with only few mode shapes. In the current paper only a subset of modes is taken into account. In particular our interest lies within the lower frequency range and thus the first two or three modes in the Fore–Aft (FA) or Side–Side (SS) direction are considered. The aforementioned can be expressed as follows:

$$\boldsymbol{x_{FA}}(t)=\Phi_{FA}\boldsymbol{q_{FA}}(t) \tag{5}$$

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