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Dynamic strain estimation for fatigue assessment of an offshore monopile wind turbine using filtering and modal expansion algorithms

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ABSTRACT

Offshore wind turbines are exposed to continuous wind and wave excitation. The monitoring of high periodic strains at critical locations is important to assess the remaining lifetime of the structure. At some critical locations below the water level, direct measurements of the strains are not feasible. Response estimation techniques can then be used to estimate the strains from a limited set of response measurements and a system model. This paper compares a Kalman filtering algorithm, a joint input-state estimation algorithm, and a modal expansion algorithm, for the estimation of dynamic strains in the tower of an offshore monopile wind turbine. The algorithms make use of a model of the structure and a limited number of response measurements for the prediction of the strain responses. The strain signals obtained from the response estimation algorithms are compared to the actual measured strains in the tower.

1. Introduction

Offshore wind turbines (OWTs) are exposed to continuous wind and wave excitation and loads originating from the rotor, a.k.a. rotor harmonics. These cyclic loads and their interaction with the turbine dynamics make fatigue life a design driver for offshore wind turbines. The continuous monitoring of the strain response time histories at fatigue hot spots, e.g. at the mud-line, is important to assess the remaining lifetime of the structure. For (offshore) wind turbines, two distinctive components in the strain response time history and consequently in the fatigue spectra can be identified. The low-frequent, near-static (<0.5 Hz) strain cycles are related to variations in the thrust loading of the turbine, e.g. due to gusts. This component can be estimated using the 1 Hz turbine SCADA-data [1] and thus in theory requires no direct strain measurements. The second component is linked to the turbine's dynamics and modal behavior. The corresponding dynamic strains are associated to a higher frequency-range (>0.1 Hz) and contain additional sources of vibrations, such as turbulence, rotor harmonics, and wave-loading. These strain components are currently best determined using direct measurements of the strain. For some critical locations such a direct measurement is not feasible. For example, direct measurements of the strains at the mud-line require sensors installed prior to the pile-driving of the monopile foundation. As a

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consequence, the sensors cannot be installed on existing OWTs. Experience in the field has also shown that strain sensors are harder to maintain, are less reliable than accelerometers over long periods in time, and are more susceptible to installation errors.

When direct measurements of the strains are impossible, fatigue monitoring of a wind turbine over its lifetime can be performed (a) through estimation of the dynamic loads applied to the structure (force identification), or (b) through model-based extrapolation of a limited set of available response measurements (response estimation). Many algorithms for force identification have been proposed in the literature [2–5]. A time-domain deconvolution approach was applied in [6] for the estimation of wind loads on a 50 m tall mast. Recently, various Kalman filter-based force identification techniques have been proposed [7–11]. These techniques allow for online reconstruction of the dynamic loads applied to a structure. Hwang et al. proposed the identification of wind loads in the modal space, through the combined use of the Kalman filter and recursive least-squares estimation [12]. The approach was verified using wind tunnel experiments in [13]. A slightly modified version of the algorithm proposed in [12] was used by Niu et al. [14] to reconstruct the wind loads on the Canton tower. Klinkov and Fritzen [15] adopted a robust observer technique for estimating the wind loads on a 5 MW wind turbine. This technique applies to both linear and nonlinear systems.

Response estimation techniques can be used to estimate the strains from a limited set of response measurements (accelerations, strains, etc.) and a system model. Various approaches for the estimation of stresses and strains using response estimation techniques are presented in the literature. Hjelm et al. [16] presented a strain estimation technique often referred to as modal expansion or full-field strain prediction [17]. This technique was further explored in [18] and was validated for predicting accelerations on an OWT in [19]. Other approaches make use of time varying auto-regressive models [20] and Kalman state estimation. The latter approach was introduced in the field of structural dynamics by Papadimitriou et al. [21], where acceleration measurements are used as input to the Kalman filter to obtain the strain at unmeasured locations. Smyth and Wu [22] used the Kalman filter for the fusion of displacement and acceleration data obtained at different sampling rates. The displacement signals obtained after fusion are found to be more accurate than the original displacement data. The Kalman filter based response estimation was investigated numerically and experimentally in [23], for the special case of excitation characterized by low frequency variations. The paper also explores the advantages of data fusion, i.e. the simultaneous integration of multiple types of measurements, for example acceleration and strain measurements. It was numerically verified by Jo and Spencer [24] that the combination of acceleration and strain data in conjunction with the Kalman filter results in better estimates compared to the ones obtained from the sole use of acceleration or strain data.

In cases where state estimation is performed for nonlinear or uncertain dynamic systems, e.g. systems with time varying characteristics, the standard Kalman filter can no longer be applied for state estimation. Several extensions of the Kalman filter for nonlinear dynamic systems have been proposed. One well known application in the literature is the simultaneous estimation of the system states and unknown system parameters, which is referred to as joint state and parameter estimation. Some commonly used algorithms for joint state and parameter estimation are the unscented Kalman filter (UKF) [25,26], the extended Kalman filter (EKF) [27], and the particle filter [25,28]. A comprehensive overview of the current state-of-the-art can be found in [29]. The extensions of the Kalman filter for nonlinear systems are not further considered in this paper.

Verification of dynamic strain estimation using filtering techniques so far is mostly based on numerical simulations, where measurement errors are introduced by adding white noise to the simulated response signals, or on laboratory experiments. This paper presents a full-scale verification of two filtering algorithms and a modal expansion algorithm, using data obtained from in situ measurements on an offshore monopile wind turbine in the Belgian North Sea [30]. The first algorithm is a Kalman filtering algorithm. The second algorithm is a joint input-state estimation algorithm that was originally proposed by Gillijns and de Moor [31], introduced for response estimation in structural dynamics by Lourens et al. [32], and applied to a (simulated) offshore wind turbine structure in [33]. The algorithm is further extended in [34] for application in presence of unknown stochastic excitation when accelerations are measured. The third algorithm is a state-of-the-art modal expansion algorithm [16,18,19]. The response estimation algorithms make use of a model of the structure and a limited number of response measurements for the prediction of the dynamic strain in the tower of the turbine. The system model used in the strain estimation is constructed based on the mode shapes and natural frequencies obtained from a finite element model of the structure and the damping characteristics that are obtained from a prior operational modal analysis (OMA). The data used in the response estimation consists of accelerations and strains. The focus of the paper is on dynamic strain estimation. The estimation of low-frequent, near-static strain components is not considered.

The outline of the paper is as follows. In Section 2, the two filtering algorithms and the modal expansion algorithm, as well as their application for response estimation are briefly recapitulated. Next, Section 3 shows the verification of the proposed response estimation techniques using data obtained from a monitoring campaign on a monopile offshore wind turbine. Section 4 defines the future work that directly results from the work presented in this paper. Finally, in Section 5, the work is concluded.