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Fatigue analysis of floating wind turbine support structure applying modified stress transfer function by artificial neural network

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ABSTRACT

The frequency-domain approach has been studied as a potential replacement modality for the time-domain method in fatigue analysis of offshore wind turbine structures. It is assumed that in the frequency-domain approach, the stress response spectra induced by wind and wave loads can be expressed by a stress transfer function. To obtain the stress transfer function, coupled analysis should be performed in advance. However, since the response of a wind turbine to different average wind speeds is non-linear, the stress transfer function is bound to change with wind speed. This means that repeated simulation is needed in order to calculate the stress transfer function according to wind speed change. The problem, though, is that if the number of simulations is large, prohibitively high computational and time costs probably will be incurred. In this study, to reduce the number of simulations and, at the same time, increase the accuracy of results, a correction factor of the stress transfer function induced by wind load was artificial-neural-network-approximated as a function of mean wind speed and frequency. Sensitivity analysis was conducted to determine how many sample points are required and how to select them. Also, a superposition model is proposed to improve the accuracy of the ANN model. This model is designed so that the peaks in the stress spectrum have a dominant influence on fatigue damage. In order to better simulate the correction factor around the peak, the model considering only the data of the periphery of the peaks and the model reflecting the whole data are superimposed. The total stress spectrum were calculated by summing stress spectrum induced by wind load from the ANN model and induced by inertia load from motion analysis based on linear wave theory. Numerical analysis for a 10 MW class wave and offshore wind hybrid power generation (WWHybrid) system, which is a kind of semi-submersible wind turbine platform, was performed to verify the performance of the proposed model. It was confirmed that the superposition model improves the accuracy by 20–50% compared with the single ANN model.

1. Introduction

Fatigue analysis of floating offshore wind turbine structures, unlike that of general offshore structures, confronts highly complex problems including the combined-wind-wave effect on platform motion, nonlinearities induced by mooring force, and large platform motion. Accordingly, fatigue analysis of such structures typically has been performed in the time domain. However, whereas it is possible to handle nonlinearities and interaction problems in the time domain, this approach incurs significant computational and time costs. Also, inherent uncertainties make single-run estimations of fatigue damage more difficult, thus requiring repeated simulations. Time-domain analysis at the initial design stage is also difficult, given the thousands of combinations of environmental conditions that must be considered. Therefore, time-domain fatigue analysis is performed only in limited-load cases that are assumed to represent whole-load combinations in actual practice.

In order to make fatigue analysis of wind turbine structures more efficient, the frequency-domain approach has been developed. This method assumes that there is a linear relationship between environmental parameters such as wind speed or wave amplitude and structural responses. The relationship is expressed as a transfer function. There are two main load sources acting on floating wind turbine structures: wind and waves. Thus, in fatigue analysis of floating wind turbines, stress transfer functions induced by both wind and wave loads should be estimated.

An integrated frequency-domain method for the support structure of a

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fixed monopile wind turbine was proposed by Van Der Tempel (2006). In his method, wind and wave loads are handled separately, and the interaction effect between the two loads is considered only by aerodynamic damping. When the wind-load-induced stress transfer function is calculated, the platform is fixed to eliminate the effect of the wave load. On the other hand, the aerodynamic damping, which means the damping effect induced by wind load on platform motion, is applied in calculation of the stress transfer function by wave loads. This method yields quite accurate results where the interaction effect between wind and waves is quite small, as in the case of a fixed platform. In a floating wind turbine structure, however, where the interaction effect is strong, it might no longer be reasonable to consider wind and wave loads separately.

Ragan and Manuel (2007) compared equivalent fatigue loads calculated by conventional time domain method and Dirlik's spectral method. They pointed out that Dirlik's spectral method could be useful for predicting fatigue loads for some but not all turbine responses especially edge bending moment. They also explained that spectral method almost gave more conservative results than conventional rainflow counting method.

A floating wind turbine structure's motions as calculated by time- and frequency-domain simulations were compared by Philippe et al. (2011). The time-domain simulation, conducted by FAST, used an aerodynamic and wind turbine model that was not linearized; in the frequency-domain simulation, by contrast, the whole system was linearized. The frequency-domain simulation relative to the time-domain simulation, accordingly, yielded quite accurate frequency response operators. The authors also pointed out deviations of around 0.3 rad/s in the sway, roll and yaw motions that could have been caused by the aerodynamic and turbine model's non-linear effects.

Response analyses of a wind turbine installed in tension leg platform were performed by Bachynski and Moan (2012) using time- and frequency-domain methods. The frequency-domain method provided reasonable results only for the wave-only condition, especially in a mild sea. When the wind load was applied, the low-frequency components of surge and pitch increased and excited some motion at the 1st pitch natural frequency.

The study on optimization of catenary mooring system for floating wind turbines was performed by Brommundt et al. (2012). They applied the frequency domain approach to reduce computation cost and time by using the linearized mooring stiffness matrix and spectral loading matrices. They pointed out that the importance on directionality to define load cases in case of asymmetrical mooring system and low-frequency contributions form wind could lead to excitations in platform pitch.

A method for fatigue analysis of a semi-submersible-type floating wind turbine structure was developed by Kvittem and Moan (2015). They investigated tower fatigue damage considering the first flexible mode of the turbine tower. Unlike Van der Tempel, they reflected structural flexibility by modeling the tower base as a rotation spring and mass for calculation of the stress transfer function by wind load. Their wave-only analysis showed good agreement between the frequency- and time-domain results, whereas their wind-wave analysis indicated that the frequency-domain method tended to underestimate fatigue damage by as much as 60%.

Merz (2015) developed a set of codes for describing the linearized aeroelastic dynamics of an offshore wind turbine. To verify the codes, he compared some turbine responses like natural frequencies, damping ratios and transfer functions calculated other commercial codes.

Zwick and Muskulus (2016) performed regression analysis on fatigue damage of a jacket-type support structure considering wind and wave loading to reduce the number of load cases while retaining a high level of accuracy. They used a piecewise linear function and multivariate linear statistical model to express the fatigue damage of each load cases as a function of wind speed. Through case study for jacket structure, they verified that the method could reduce the number of simulation from 21 to 3 as retaining the accuracy within 6%.

A stress transfer function by wind load is calculated from time-simulation time-series data for a specified mean wind speed. Because turbine responses have non-linear relationships with mean wind speed, the stress transfer function should vary under different mean wind speeds. As mean wind speed increases, more energy is concentrated on the 1st natural frequency of the support structure (Van Der Tempel, 2006). This means that for precise fatigue damage estimation, the stress transfer function by wind load should be estimated with every mean wind speed in a wind scatter diagram. And in order to obtain those stress transfer functions, time-domain analysis would have to be performed in advance, which could be time-consuming work.

In the present study, for the purpose of reducing the number of required time simulations and increasing the accuracy of results calculated by the frequency-domain approach, a regression analysis of a correction factor defined as the ratio of the stress transfer function by wind load at a specific wind speed to the stress transfer function at the rated wind speed was performed using the artificial neural network (ANN) algorithm. The proper input and output variables of the ANN model are suggested, and its optimal structure is discussed. A study to determine the sampling strategy for the training process in construction of the model is performed.

The effect of each frequency component on fatigue damage in the stress spectrum is not equal. The frequency component around the peak has a large spectral density, which has a great influence on fatigue damage, while the other components each have a relatively small influence. A single ANN model trained with the whole data cannot easily reflect these weights and, thus, can impair the accuracy of the final result in order to reflect the less important data in the model. To overcome this problem, this paper proposes a superposition model constructed by superimposing a model that considers the entire data with models trained only for the peak periphery data. In other words, the influence of other data is excluded in the periphery of the high-importance peak. The performance of this proposed model was verified, in the present study, by numerical analysis of a semi-submersible-type floating wind turbine.

The contents of this paper are as follows. In Section 2, the ANN model's input and output variables are introduced, and its optimal structure is determined by comparing several models. Section 3 summarizes the procedure for constructing the ANN model and applying it in the frequency domain to a fatigue analysis on offshore wind turbine support structures. Finally, Section 4 provides a numerical example of the proposed method in a semi-submersible type structure.

2. Artificial neural network (ANN) approximation for stress transfer function

According to the nonlinearity of turbine responses to different mean wind speeds, a wind-induced stress transfer function varies. Obtaining the stress transfer function from time simulations in fatigue analysis requires dozens of simulations to handle thousands of environmental conditions. This is also time-consuming work, as a fully coupled time simulation entails estimation of the stress transfer function with each mean wind speed within a wind scatter diagram's range, which process takes a couple of days to perform. As a means of reducing the required number of simulations, regression analysis can be effective. One of useful tools for estimation of a function that depends on many input variables is the ANN model. Indeed, it has been widely adopted to solve problems in the field of ocean engineering. The time series of an FPSO's motions was calculated by Mazaheri (2006) using an ANN model. Uddin et al. (2015) introduced various offshore-fixed-platform applications of ANN models ranging from damage detection to jacket controls.

2.1. Correction factor for stress transfer function by wind load

In frequency-domain fatigue analysis of wind turbine support structures, several inputs and outputs are needed [Fig. 1]. For example, a stress response amplitude operator (RAO) or a stress transfer function is a