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Wide-banded fatigue damage evaluation of Catenary mooring lines using various Artificial Neural Networks models

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ABSTRACT

Catenary mooring lines used in floating offshore platforms are a representative structural part that undergoes a wide-banded tension process due to low frequency drift forces and high frequency wave forces. Time domain analyses are the best way to determine a representative fatigue damage under a wide-banded process, but the time domain analysis can be computationally expensive. This paper reports a functional relationship between the environmental conditions and probability density function (PDF) of tension distribution using an Artificial Neural Network (ANN), which can be used to reduce computational cost with reasonable accuracy when compared to the time domain approach. The predictive accuracy of the fatigue damage under wide-banded process is dependent on how well the PDF of the process is defined. This study addresses three approaches in expressing the distributions: superposition of multiple Gaussian distribution functions (Superposition approach), direct prediction of the distributions (Piecewise approach), and n^{th}-order moments of the distributions (Moment approach). A full-scale floating offshore wind turbine (FOWT) platform was used for the target structure with three catenary mooring lines. The sea state data collected from the Jeju offshore area in Korea were used as the input data for the time-domain mooring dynamics analyses of the FOWT as well as input neurons of the three multi-layered ANN models. The tension distributions in each mooring line were used for the three types of output neurons in terms of the PDF parameters for the Superposition approach, a certain number of distribution points for the Piecewise approach, and moment values for the Moment approach. The accuracy of each trained ANN was verified by comparing the predictions by the trained ANN with the hydrodynamic simulation results for the newly defined load cases. It was proven that the Moment approach-based ANN model predicts the wide-banded fatigue damages most consistently.

1. Introduction

Environmental pollution is a critical byproduct associated with the development of offshore oil exploration, production, and transportation activities. Consequently, the demands for marine renewable energy technologies that have significantly less environmental impact are in growing demand. Floating offshore wind turbine (FOWT) platforms are a representative class of marine renewable energy structures. The FOWT platform requires a mooring system to control horizontal offset from a mean or still water position during power production as a result of environmental conditions.

The mooring system is designed to withstand harsh environmental loads comprising of wave, wind, and current in extreme

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(storm) conditions. In addition, the mooring lines are subjected to wide-banded tension loads as a result of excitation by wave-induced high frequency loads and restoring force-induced low frequency loads.

Time domain analysis is recognized as the most representative method for calculating wide-banded fatigue damage as a wide-banded process is not well presented by the Rayleigh PDF or any other combination of different PDFs in frequency domain analysis. In addition, linearized response derived by frequency domain analysis is not applicable to systems where there is any significant degree of non-linearity, such as a catenary system in moderate environmental conditions. Wirsching and Light [1] proposed a correction factor multiplied to narrow-banded fatigue damage to consider the wide band effects of waves. Benasciuti and Tovo [2] performed a series of wide-banded hydrodynamic analyses to advance a correction function. Jiao and Moan [3] proposed a challenging methodology that combines a fully separated low- and high-frequency narrow banded-spectrum to calculate a correction factor. Dirlik [4] presented a PDF composed of an exponential PDF and a Rayleigh PDF. Similar to the approach by Dirlik [4], Zhao and Baker [5] also presented a PDF which was a combination of a Weibull PDF and a Rayleigh PDF. Park et al. [6] also proposed a new PDF to estimate the wide-banded process and detailing the development process of the PDF. These approaches, whether based on correction factors, a combination of spectra, or the development of a new PDF cannot be applied universally to problems with a wide-banded spectral form.

Therefore, a new technique is necessary to effectively evaluate the wide-banded fatigue damage of mooring lines. An artificial neural network (ANN) is an effective means of predicting fatigue damage provided that it is sufficiently well trained. ANN models are one of the most useful methods that can be applied to problems that are difficult to formulate mathematically. Venkatesh and Rack [7] demonstrated an ANN application for predicting the creep fatigue life at elevated temperatures. Haque and Sudhakar [8] developed an ANN to predict the fracture toughness and tensile strength as a function of the microstructure. Kalra et al. [9] applied a trained ANN to predict the significant wave heights at a specified coastal site using database gathered by a satellite at deeper offshore locations. Kang et al. [10] used an ANN to predict the multiaxial fatigue life at critical locations of an automotive sub-frame under a multiaxial random loading. Pina et al. [11] proposed an ANN based on surrogate models to obtain the tensions in the mooring lines and risers. Li and Choung [12] applied ANNs to predict wide-banded fatigue damage in the mooring lines of an FOWT and verified that a well-trained ANN could provide a solution consistent with time domain results.

This paper is an extension of the study by Li and Choung [12], who used an ANN to predict wide-banded fatigue damage employing a Piecewise approach using environmental conditions and piecewise points of the tension distribution in the moorings as input and output neurons, respectively. This required the number of piecewise points for the tension distribution to be the same as the number of output neurons. However, increasing numbers of piecewise point exponential increased training time, resulting in an ANN model that required a very long training time.

This paper presents an ANN model based on the superposition of multiple Gaussian distribution functions, hereafter it is called Superposition approach. A second approach that is based on a direct prediction of the mooring line tension distribution as in the study by Li and Choung [12] is presented this is referred to as the Piecewise approach. A third ANN model that is based on the n^{th}-order moments of the tension distribution, and denoted as the Moment approach is also shown. Li and Choung [12] used OC4 (Offshore Code Comparison Collaboration Continuation) 5 MW FOWT [13] as the basis of their study. This study introduces the 8 MW FOWT structure, that is similar to the well-known WINDFLOAT FWOT 2 [14]. ANSYS/AQWA [15] is used to generate time domain hydrodynamic results in mooring line and an ANN module provided by MATLAB [24] is applied to train ANN model for further application. The metocean (wave, current, and wind) data used in this study were collected from the Jeju area offshore South Korea. The average wind speed in this region is known to be favorable for FWOT. The collected environmental conditions were not only used as input for time domain hydrodynamic analyses but were also forwarded to the input neurons of each ANN model. The PDFs derived from time domain hydrodynamic analysis were used as output neurons. Some parts of the time domain hydrodynamic results were used to train the ANN model until they produce outputs that were close enough to the desired output, optimizing the weights and bias of the ANN model. Fatigue damage predictions from three trained ANN models for the new environmental conditions were compared with those determined by time domain fatigue analyses.

2. Hydrodynamic analyses

2.1. Frequency response analysis

The WINDFLOAT2-type 8 MW FOWT platform consisted of three circular stabilizing columns that form an equilateral triangle, connected together by horizontal and diagonal tubular bracings. Water entrapment plates (WEPs) are attached to the bottom of the columns to suppress heave, roll, and pitch motions, as shown in Fig. 2(a). Geometric details for the columns, WEPs, and bracings are shown in Fig. 2. The turbine tower with a diameter of 11.5 m is placed on column #1 (see Fig. 1). Table 1 lists the detailed mass properties of the FOWT platform. All geometry and mass details were taken from the results of a joint industry project in which they were newly calculated based on the hydrostatic and simple beam calculations.

Fig. 2(a) and (b) depicts the dimensions of the floating platform and the hydrodynamic model generated from the structure with the non-diffraction elements for the dry part (above the mean water level) and diffraction elements for the wet part, respectively. The three water entrapment plates were also modelled using the diffraction element. Tube elements that are capable of simulating only Morison forces were modelled for the horizontal braces (H-Brace in Fig. 2(a)) and diagonal braces (D-Brace in Fig. 2(a)). A point mass containing lumped mass information, as described in Table 2, is located at the center of mass (COM). A commercial hydrodynamic analysis code, ANSYS/AQWA [15] herein referred to as AQWA, was used to perform the hydrodynamic analysis in this study. Table 2 summarizes the types and numbers of the used element for each part.