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Critical assessment of non-linear hydrodynamic load models for a fully flexible monopile offshore wind turbine

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ABSTRACT

This paper presents a comparison between experimental data of a model-scale 4 MW monopile offshore wind turbine subjected to extreme irregular sea states in finite water and the numerical models suggested in offshore wind energy standards to assess ULS conditions. The model is fully flexible with its 1st and 2nd eigenfrequencies and 1st mode shape tuned to fit those of the full-scale turbine. The measured and simulated bending moments at the sea bottom are decomposed around the eigenfrequencies of the structure, and the Morison equation with stream function wave kinematics is found to trigger transient 1st mode response (so-called ringing response). The amplitude of the simulated 1st mode response is proportional to the incoming wave steepness; such a relationship is not observed experimentally. Similarly, 2nd mode response is triggered by Wienke's slamming model, but generally does not match the experimental data. Although the numerical models from the design standards (Morison's equation with stream function kinematics, plus a slamming model) can give conservative estimates of the extreme responses, the models miss the balance between 1st and 2nd mode responses. The simplification of the physics in the numerical models can thus lead to inaccuracies in response prediction, such as the stress distribution along the monopile.

1. Introduction

Offshore wind turbines mounted on monopiles are currently being built or planned in the North Sea in water depths between 20 and 50 m (Ho et al., 2016). In order to safely design the monopiles, the maximum load effect that the structure will experience over its lifetime has to be assessed (so-called Ultimate Limit State (ULS) analysis). A number of standards suggest hydrodynamic load models for such a study for different situations (for example DNV-OS-J101, 2014; DNV-RP-C205, 2014a; IEC 61400-3, 2009). These standards are mostly adapted from experience from the oil and gas industry, whose structures differ from offshore wind turbines in two important aspects:

- The depths considered for oil and gas platforms are much larger than those of offshore wind turbines, enabling the simplification of 'infinite water depth'.
- For offshore wind turbines, the displacement of the 2nd mode shape near the mean sea level is large compared to oil and gas platforms. This means that the 2nd mode of the structure will be excited by breaking wave events (which induce loads around the mean sea level), as shown for instance by Peeringa and Hermans (2017). For bottom-fixed oil and gas platforms, breaking wave loads act close to the maximum of the 1st mode shape, but are unlikely to excite global 1st mode response due to the short load duration.

Fig. 1 illustrates the concepts explained above. The largest contribution from hydrodynamic loads is around the mean sea level, which means that for a wind turbine it will be low (in relative heights) compared to an offshore oil and gas platform.

The main aim of this paper is to assess how well the standards used by the offshore wind industry predict the response of the support structure in ULS conditions. Experimental data produced by the Maritime Research Institute Netherlands (MARIN) is compared to the numerical models proposed in the standards. In these experiments, a fully flexible model of an idling 4 MW bottom-fixed offshore wind turbine mounted on a monopile was subjected to extreme weather conditions. Suja-Thauvin et al. (2017) analysed these experiments and showed that the largest responses for an offshore wind turbine in the above-mentioned conditions were provoked by steep and breaking waves. 2nd and 3rd order hydrodynamic loads from the wave trigger the 1st mode of the structure and produce the response phenomenon known as 'ringing', characterized by a build-up of the resonant vibration over about one wave period which then slowly decays (Natvig, 1994) and illustrated in Fig. 2. The bending moment in Fig. 2 has been

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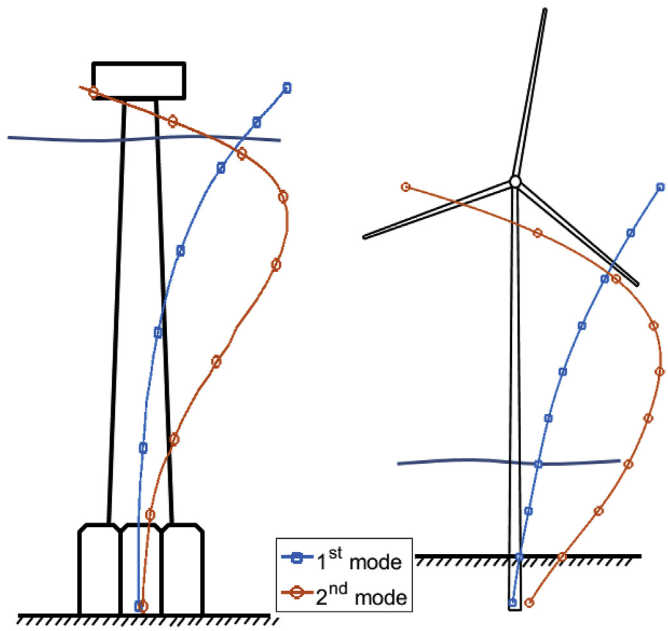

Fig. 1. Schematic representation of the Draugen platform (Natvig and Teigen, 1993) and the offshore wind turbine used in the present paper (not to scale). The lines represent the 1st and 2nd mode shapes normalized against their maximum value (the mode shapes of the Draugen platform are taken from Faltinsen and Timokha, 2016).

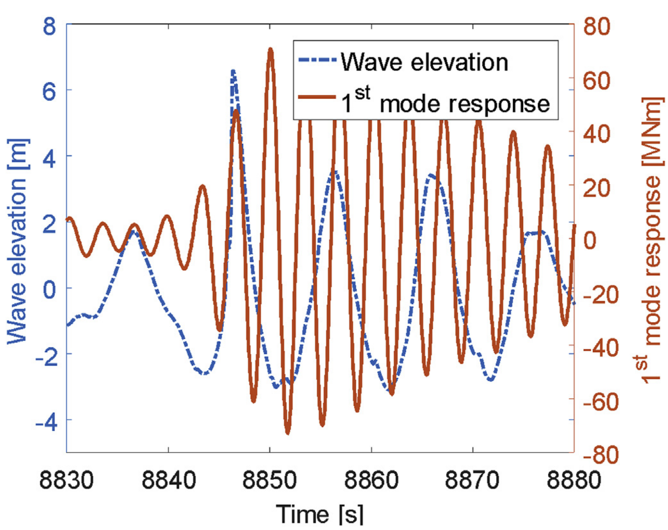

Fig. 2. Illustration of a ringing event. A surface-piercing vertical cylinder is exposed to a steep wave, and the bending moment is measured at the sea bottom.

filtered to show only the response of the 1st mode of the structure, this procedure is explained in section 5.2. The loads due to the impact of the breaking wave on the structure (so-called slamming loads) excite the 2nd mode of the structure, which can account for up to 20% of the maximum response (Suja-Thauvin et al., 2017). Slamming loads excite all modes of the structure, but only higher modes will be significantly excited due to (i) the very short slam duration compared to the 1st eigenperiod and (ii) the shape of the 2nd mode compared to the 1st mode. A conclusion of Suja-Thauvin et al. (2017) is thus that in order to correctly depict the maximum responses experienced by the support structure of offshore wind turbines, one has to account for both ringing responses and responses to breaking waves.

Numerical models for predicting ringing gained attention in the 1990s, when ringing was first observed during model tests of the Hutton and Heidrun TLP offshore oil and gas platforms and of the deep water concrete towers of the Draugen and Troll A platforms (Natvig and Teigen, 1993). For offshore wind turbines, the necessity of using non-linear wave kinematics when calculating hydrodynamic loads for capturing this phenomenon was shown for example by Marino et al. (2013a). This agrees well with Paulsen et al. (2013), who showed by using a CFD solver that the excitation force based on linear wave kinematics does not have the frequency content necessary to excite the 1st mode of the structure. Bredmose et al. (2012) used a simple cantilever beam numerical model to assess the importance of wave height and water depth with respect to ringing responses and to show how this phenomenon can dominate the total response due to dynamic amplification.

In addition to ringing responses, breaking wave events have also been studied for offshore wind turbines. Both de Ridder et al. (2011) and Bredmose et al. (2013) carried out experiments on a bottom-fixed responding structure whose characteristics were similar to those of an idling extra-large wind turbine and found out that breaking waves could lead to extreme accelerations of the nacelle. Bredmose and Jacobsen (2010) carried out a CFD analysis where focused waves were forced to break at different locations in the vicinity of the turbine in order to assess the hydrodynamic loads at different stages of the breaking process. Marino et al. (2013a) applied a fully nonlinear high-order boundary-element solver to a series of realistic sea states and showed that the bending moment at the tower base could be six times larger compared to a linear model.

The numerical models presented in the aforementioned works provide accurate predictions of the response of a bottom-fixed offshore wind turbine to steep breaking waves but are too computationally expensive to be used by the industry for design, where typically thousands of load cases need to be assessed. The standards commonly used by the industry to calculate hydrodynamic loading under steep breaking waves (DNV-OS-J101, 2014; DNV-RP-C205, 2014a; IEC 61400-3, 2009) suggest simpler models, such as the stream function theory (Rienecker and Fenton, 1981) and Wienke's slamming model (Wienke and Oumeraci, 2005). To assess the validity of these models for calculating the turbine's response under steep/breaking wave loads, the above-mentioned models have been implemented in Matlab® and used to try to match the experiments carried out by MARIN.

Other theories that attempt to reproduce ringing responses have been developed by Faltinsen et al. (1995), so-called FNV model, and Malenica and Molin 1995, so-called MM model. Both these theories were developed based on a perturbation approach and estimate the excitation load up to third order in terms of wave steepness. Krokstad et al. (1998) presented a validation of the response predicted by the FNV model in deep water, and Kristiansen and Faltinsen (2017) further developed the model for finite water. Paulsen et al. (2014) showed that the 3rd order excitation loads from both the FNV and the MM models, within their range of validity, match those predicted by CFD. Both models account for hydrodynamic-structural interaction by considering the diffracted wave from the cylinder. On the contrary, the models presented in this paper – and commonly used in design – do not account for the presence of the structure, and only estimate the kinematics of the undisturbed wave.

The paper is organized as follows: section 2 briefly presents the experiments carried out by MARIN, and in section 3 we introduce the structural model used in the paper. In section 4 we use the models proposed by the standards to carry out the ULS analysis under the environmental conditions of the MARIN experiments, and section 5 compares the same models on a single event basis to assess how the models perform. Conclusions are drawn in section 6.

2. Presentation of the model test

A more detailed description of the experiments is given by Suja-Thauvin et al. (2017); only the most relevant points are given here. The