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Experimental results of a multimode monopile offshore wind turbine support structure subjected to steep and breaking irregular waves

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A R T I C L E I N F O

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A B S T R A C T

We present experimental data from MARIN on a bottom-fixed offshore wind turbine mounted on a monopile in intermediate water depth subjected to severe irregular wave conditions. Two models are analysed: the first model is fully flexible and its 1st and 2nd eigenfrequencies and 1st mode shape are representative of those of a full-scale turbine. This model is used to study the structural response with special focus on ringing and response to breaking wave events. The second model is stiff and is used to analyse the hydrodynamic excitation loads, in particular the so-called secondary load cycle. The largest responses are registered when the second mode of the structure is triggered by a breaking wave on top of a ringing response. In such events, the quasi-static response accounts for between 40 and 50% of the total load, the 1st mode response between 30 and 40%, and the 2nd mode response up to 20%. A statistical analysis on the occurrences and characteristics of the secondary load cycle shows that this phenomenon is not directly linked to ringing.

1. Introduction

Over their lifetime, many bottom-fixed offshore wind turbines will encounter steep or breaking waves that might produce large structural responses. A number of offshore wind farms are planned or being developed in the North Sea, in water depths between 20 and 50 m (Ho et al., 2016). At these depths, interaction with the sea bottom enhances the wave nonlinearity, increasing the likelihood of breaking waves (Dalrymple and Dean, 1991). When designing the support structure of an offshore wind turbine for a specific site, the industry has to assess the maximum expected response that the structure will experience over its lifetime (so-called Ultimate Limit State (ULS) analysis, DNV, 2014a; DNV, 2014b; IEC, 2009).

Under ULS conditions, experiments have shown that the natural period of the structure can be suddenly excited by non-breaking waves whose fundamental period lies far from the structure's eigenperiod (Marthinsen et al., 1996; Stansberg et al., 1995; Welch et al., 1999). This phenomenon, called ‘ringing’, is characterized by a fast build-up of transient resonant vibrations (only a few oscillations; Chaplin et al., 1997) and a much slower decay (Natvig and Teigen, 1993). In the case of a monopile type of support structure such as the one studied in this paper, ringing occurs during the passage of steep waves whose height is of the same order of magnitude as the diameter of the cylinder and whose fundamental period is around 3 times the natural period of the structure. Fig. 1 shows an illustration of a ringing event. The bending moment has been filtered to show only the response of the first mode of the structure (this procedure is explained in section 4). After the passage of a very steep wave, the first mode gets suddenly excited and then decays slowly.

The ringing phenomenon started gaining attention in the 1990s when it was first observed on model tests of the Hutton and Heidrun TLP offshore oil and gas platforms, and then on the deep water concrete towers of the Draugen and Troll A platforms (Natvig and Teigen, 1993). Recently, the increase in size of offshore wind turbines combined with the limitation of the blade tip velocity has led to decreasing natural frequencies of the support structure down to a level where the 3rd harmonic of large waves (i.e. three times the fundamental frequency) coincides with the first structural natural frequency. This intensifies the risk of ringing response when subjected to extreme storms (see Suja-Thauvin et al., 2014). In addition to higher order hydrodynamic loads, breaking wave events have been a major concern for offshore structures. Both de Ridder et al. (2011) and Bredmose et al. (2013) carried out experiments on a bottom-fixed responding structure (as opposed to a stiff structure) whose characteristics were similar to those of an idling extra-large wind turbine (i.e. with the blades completely pitched to feather to limit the aerodynamic loading) and found that breaking waves could lead to extreme accelerations of the nacelle.

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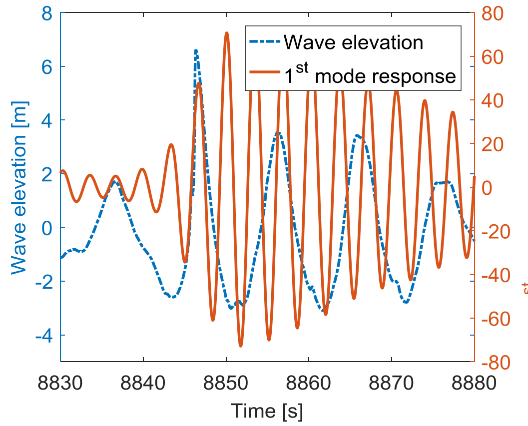

Fig. 1. Illustration of a ringing event. A surface-piercing vertical cylinder is exposed to a steep wave, and the bending moment is measured at the sea bottom. The 1st mode is suddenly triggered and slowly decays, which is a typical characteristic of ringing events.

The main objective of this paper is to examine the process of maximum response of monopile offshore wind turbines under extreme stochastic sea states, in particular assessing the importance of the second mode of the structure and the characteristics of the measured excitation. In order to do so, we analyse data from experiments carried out in the Maritime Research Institute Netherlands (MARIN). The tests were performed within the project Wave Impact on Fixed structures (WiFi JIP). The characteristics of the model used for the experiments are those of an idling 4 MW bottom-fixed offshore wind turbine mounted on a monopile. These tests were performed with both a flexible and a stiff model in order to be able to measure the response and the excitation of the structure. Here, we focus on the measured excitation and response rather than on the wave kinematics. A correct understanding of the most important physical effects is an important first step in developing and validating engineering models which incorporate the relevant nonlinearities in the wave kinematics and in the wave-structure interaction.

In addition to the response analysis, we examine the phenomenon known as "secondary load cycle", or SLC, which appears as a rapid and high frequency increase of the excitation force, as Grue et al. (1993) described from their experiments. An occurrence of a SLC (sometime referred to as 'hydraulic jump') is highlighted in Fig. 2. The SLC typically occurs about one quarter wave period after the main peak of the excitation force (Grue and Huseby, 2002) and lasts for about 15% of the wave period (Grue et al., 1993).

Occurrences of SLCs have been extensively reported for steep waves

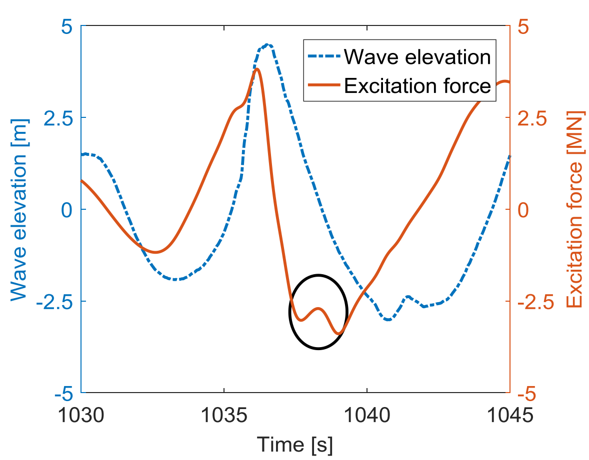

Fig. 2. Occurrence of secondary load cycle, visible on the excitation force (circled in black).

in experiments in infinite water depths (see Chaplin et al., 1997; Grue et al., 1993; Grue and Huseby, 2002; Stansberg et al., 1995; Welch et al., 1999). Grue and Huseby (2002) also summarized the experimental data from those papers to establish a trend of occurrences of the SLC. One of their conclusions is that flow separation effects might reduce the likelihood of SLCs on small cylinders, and they suggest that for experimental analysis of the SLC the β-number should be larger than 15 000 ($\beta = (2R)^2/\nu T$, with R the cylinder radius, T the local period of the wave, and ν the kinematic viscosity of the water). For the events presented in this paper, the longest wave corresponds to $\beta \approx 19\,000$ and the Keulegan-Carpenter number is approximately 5, which places us in what they describe as cylinders of moderate size.

There has been a lot of work published around the relevance of the SLC for ringing responses. Grue and Huseby (2002) used the experimental data of the above-mentioned papers to show that SLCs and ringing responses are correlated, and state that "The secondary load cycle gives an important contribution to build-up of resonant body responses […]". High speed photography from the experiments of Chaplin et al. (1997) and Rainey and Chaplin (2003) was used by Rainey (2007) to conclude that "the rapid loading cycle causing the "ringing" vibration is traceable to local wave breaking around the cylinder […]". However, in a recent study, Paulsen et al. (2014) investigate the SLC numerically by solving the two-phase incompressible Navier-Stokes equations and conclude that "[…] the secondary load cycle is thus an indicator of strongly nonlinear flow rather than a direct contributor to the resonant forcing". This agrees with earlier findings from Krokstad and Solaas (2000), where a study of the phasing between the SLC and the ringing response led them to conclude that "The hydraulic jump [i.e. secondary load cycle] has no direct connection with the non-linear behaviour of the ringing force […]".

The paper is organized as follows: in Section 2 we describe the experimental set up and the models used during the tests and Section 3 gives a simple justification of how to estimate slamming events from video recording. Section 4 presents the analysis of the response of the flexible structure. Section 5 combines results from the stiff and the flexible structure to establish the link between secondary load cycle and ringing events. Conclusions of this study are drawn in Section 6.

2. Presentation of the model test

The model tests were carried out at 1:30.6 scale, and Froude scaling was applied in order to correctly generate gravity waves. For the considered model and wave conditions, inertia forces dominate compared to viscous forces (DNV, 2014a; DNV, 2014b; IEC, 2009) and the effects of the Reynolds number mismatch are not examined here. All the values given in the paper are full-scale unless specified otherwise.

2.1. Test facilities

The tests were performed at the shallow water basin of MARIN, a 220 m long and 15.8 m wide wave flume (model scale) with constant water depth. One end of the flume was equipped with a piston-type wavemaker, consisting of a flat plate forced into horizontal translational motion by an electrical actuator. The wave maker includes 2nd order wave generation techniques that enable a correction for the difference between the oval motion of water particles in shallow/intermediate waters and the horizontal motion induced by the flat plate. It is possible to suppress parasitic wave generation using this technique (see Schäffer, 1996). On the other side of the flume, an absorbing parabolic beach was fitted in order to minimize wave reflection. Two pits were dug into the ground approximately 65 m (model scale) from the wave maker, and the two models were mounted onto two 6-component force frames solidly anchored into the pits. Fig. 3 shows the layout of the experiment. No aerodynamic loading was modelled during the tests.