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Reliability assessment of point-absorber wave energy converters

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ABSTRACT

Ocean wave energy is a clean and inexhaustible energy resource, capable of providing more than 2 TW of energy supply worldwide. Among all the technologies available to convert wave energy, the point-absorber is one of the most promising solutions today, due to its ease of both fabrication and installation. The floaters of point-absorber WECs (wave energy converters) are generally exposed to harsh marine environments with great uncertainties in environmental loads, which make their reliability assessment quite challenging. In this work, a reliability assessment framework, which combines parametric finite element analysis (FEA) modelling, response surface modelling and reliability analysis, has been developed specifically for the floater of point-absorber WECs. An analytical model of point-absorber WECs is also developed in this work to calculate wave loads and to validate the developed FEA model. After the validation through a series of simulations, the reliability assessment framework has been applied to the NOTC (National Ocean Technology Centre) 10 kW multiple-point-absorber WEC to assess the reliability of the floater, considering the fatigue limit state (FLS). Optimisation of key design components is also performed based on reliability assessment in order to achieve target reliability. The results show that for the considered conditions, the WEC floater is prone to experience fatigue failure before the end of their nominal service life. It is demonstrated that the reliability assessment framework developed in this work is capable of accurately assessing the reliability of WECs and optimising the structure on the basis of reliability.

1. Introduction

Climate change, increasing energy demand globally, rising industrialisation, and population growth rate are just four of the driving factors that constitute clean, sustainable and renewable energy – one of the world's priorities that can enable further development. Although wind and solar energy have attracted significant attention so far, as interaction with natural resources is straightforward, in the last decade more consideration has been given to technologies harvesting energy from waves and tides. Ocean wave energy is a clean and inexhaustible resource, able to provide more than 2 TW of energy supply worldwide (Gunn and Stock-Williams, 2012). Wave energy potential has the advantages of being largely predictable and consistent topologically, as well as having high energy density, making it attractive to coastal countries (Bozzi et al., 2013; Lehmann et al., 2017).

The wave energy sector is today in the pre-commercial phase (Mørk et al., 2010) and much work is ongoing in order to raise the TRL (Technology readiness level) and then reduce the LCOE (Levelized cost of energy) (Salvatore, 2013). The device responsible for capturing and converting wave energy is the wave energy converter (WEC). This technology generally uses a PTO (power take off) system to convert the motion of the floater into electricity to the grid; the floater is one of the key parts of the whole device.

Despite the fact that many different types of WECs have been patented (Drew et al., 2009), only a few of them have been developed and installed at sea (Bozzi et al., 2013). According to the size and direction of elongation, WECs can be roughly categorised into three groups (Drew et al., 2009), i.e. 1) attenuators, in which the principal axis is parallel to the wave propagation direction; 2) terminators, in which the principal axis is perpendicular to the wave propagation direction; and 3) point-absorber, which is insensitive to wave direction due to its small dimensions relative to the incident wavelength.

Among all these different solutions, one of the most promising is the point-absorber technology. First of all, its small dimensions allow the device to be wave-direction independent and capable of absorbing power from all the wave directions, which can be highly varied during the life of the device. Additionally, this technology has the advantages of easy fabrication and installation (Drew et al., 2009; Cretel et al.,

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2011). Due to their relatively compact size, the amount of energy that conventional single point-absorber WECs can produce is relatively small when compared to other types of WECs. However, this limitation can be overcome by using multiple point-absorbers, which consist of several floaters.

In a conventional structural analysis, the material properties, environmental loads, model dimensions and parameters are deterministic quantities. This kind of analysis is reliable only in cases where randomness is relatively small. However, modern structures and more specifically those designed for offshore deployment, generally require complex designs, which are more sensitive to uncertainties, considering the environmental, operational and manufacturing processes involved. For such systems, uncertainties in design parameters should be taken into account systematically through stochastic modelling, towards a more realistic and optimised design that would consider the structure's life cycle and associated time-dependent damage mechanisms. Reliability analysis provides an effective approach for better understanding the system response to an input parameter change and hence leads to more reliable designs. In this scenario, this approach to the analysis of the WEC is needed in order to model the uncertainties arising from the high complexity of the model, its material properties, load conditions and PTO characteristics.

The methods used for structural modelling of WECs can be roughly categorised into two groups, i.e. 1) experiments, in which structural responses are measured using sensors such as strain gauges and displacement sensors; 2) FEA (Finite Element Analysis), which predicts structural responses based on numerical simulations. The first method allows the performing of direct experiments in the structure by measuring the strains of the assets considered and then assessing the related stresses. The experimental method has the advantage of being accurate as modelling uncertainty is avoided; however, it is costly and time-consuming when variability of response, due to uncertainty in design variables, is to be considered. The second approach analyses the system response through computer-simulated FEA, allowing for a wide variety of cases to be evaluated. Due to its high flexibility and fidelity, FEA has been widely used for solving complex engineering problems and is extensively applied to the structural modelling of renewable energy devices, such as wind turbine composite blades (Wang et al., 2016a, 2016b, 2016c), offshore support structures (Gentils et al., 2017; Martinez-Luengo et al., 2017) and marine structures (Nicholls-Lee et al., 2011; Tasdemir and Nohut, 2012). Therefore, FEA is chosen in this study for the structural modelling of WECs.

As far as reliability analysis methods are concerned, a series of methods with subsequent variations are available, broadly categorised into analytical and stochastic methods. Common analytical reliability analysis methods are FORM (first order reliability method) (Hohenbichler and Rackwitz, 1982) and the SORM (second order reliability method) (Der Kiureghian et al., 1987) where the limit state function is approached through Taylor's expansions and the problem of evaluating the reliability of a complex system is translated into a problem of mathematical optimisation. SORM performs better in cases of highly non-linear systems, while in other cases, the two methods give similar results (Choi et al., 2006a). With respect to stochastic methods, MCS (Monte Carlo Simulation) (Mooney, 1997) is also commonly applied, mainly due the benefits of direct simulations, hence reducing uncertainty in the results due approximations in the solutions approach, but with the constraint of calculating high probabilities for relatively non-complex engineering systems. For the nature of the problem that this work is investigating, FORM is chosen as the most appropriate method to employ.

Once the reliability assessment of the initial structure is performed for a given stochastic set of inputs, the basis for optimisation of key variables of the model is established. Starting from an initial assessment, it is possible to focus on the parts of the design that go into failure earlier and perform additional analysis to suggest modifications, avoiding failure and achieving the target reliability through a balanced system which avoids unnecessary conservatism.

To the best of the authors' knowledge, the reliability assessment of a point-absorber WEC has not been reported in the literature although reliability has been identified as a key barrier in the further development of ocean energy technologies. This paper aims to develop a reliability assessment framework for point-absorber WEC floaters and then improve the floater's initial design on the basis of reliability. A reliability assessment framework for point-absorber WEC floaters, which combines parametric FEA modelling, response surface modelling and reliability analysis is developed. An analytical model of point-absorber WECs is also developed in this work to calculate wave loads and to validate the FEA model. After the validation through a series of case studies, the reliability assessment framework has been applied to the NOTC (National Ocean Technology Centre) 10 kW multiple-point-absorber WEC to assess its reliability performance.

This paper is structured as follows. Section 2 illustrates the NOTC 10 kW multi-point-absorber WEC. Section 3 presents the analytical model of point-absorber WECs. Section 4 presents the parametric FEA model, and Section 5 details the implementation of the reliability assessment. Results and discussion are presented in Section 6, followed by conclusions in Section 7.

2. NOTC 10 kW multi-point-absorber WEC

The WEC analysed in this study is the NOTC 10 kW multi-point-absorber (see Fig. 1), designed by the NOTC of Tianjin (China) and manufactured by THOECL (Tianjin Haijin Ocean Engineering Corporation Limited). The prototype has six point-absorbers (i.e. floaters) connected to a ship-type platform for the tests. The floaters are cone-shaped and capable of capturing and converting the wave energy through their heave motion. The heave motion of each floater can pump a hydraulic cylinder to produce high pressure oil, which is then transported to the hydraulic motor through pipelines to generate electric power. The overall capacity of the WEC is 10 kW.

Fig. 2a presents the 3D (three-dimensional) geometry model of the whole system, and Fig. 2b depicts a close view of the floater.

3. Analytical model of point-absorber WECs

An analytical model of the point-absorber WECs is developed on the basis of the following assumptions:

- small wave amplitude;
- stable equilibrium of the floater;
- negligible transverse motion of the floater;
- steady-state response in waves.

Fig. 3 shows the schematic of the analytical model of the point-absorber WEC. The bar AD represents the floater arm having an angle θ with respect to the Z axis. Points A and D are pivot points offsetting

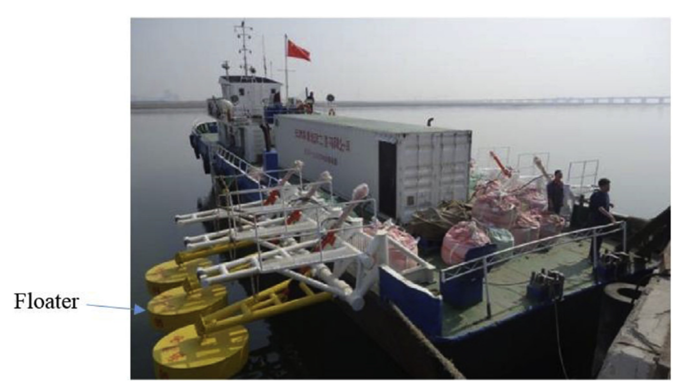

Fig. 1. NOTC 10 kW WEC.