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Full long-term design response analysis of a wave energy converter

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ABSTRACT

Efficient design of wave energy converters requires an accurate understanding of expected loads and responses during the deployment lifetime of a device. A study has been conducted to better understand best-practices for prediction of design responses in a wave energy converter. A case-study was performed in which a simplified wave energy converter was analyzed to predict several important device design responses. The application and performance of a full long-term analysis, in which numerical simulations were used to predict the device response for a large number of distinct sea states, was studied. Environmental characterization and selection of sea states for this analysis at the intended deployment site were performed using principle-components analysis. The full long-term analysis applied here was shown to be stable when implemented with a relatively low number of sea states and convergent with an increasing number of sea states. As the number of sea states utilized in the analysis was increased, predicted response levels did not change appreciably. However, uncertainty in the response levels was reduced as more sea states were utilized.

1. Introduction

Wave energy converters (WECs) must be designed to withstand a wide variety of ocean conditions. Predicting the loads and responses that a device will encounter over an extended deployment period presents a significant engineering challenge. The lack of a more trusted process for assessing survival and predicting design responses has had an adverse effect on the penetration of WECs in the energy market. Limited experience and wide variability of device archetypes (see, e.g., [1]) have restricted the ability of designers to predict design responses. The lack of a more efficient and trusted methodology for predicting design responses has hampered the penetration and development of WECs in multiple ways. In some cases, loads have exceeded the predictions of designers, resulting in device failure. However, even device designs which survive can be adversely affected by uncertainty and lack of confidence in design practices. To accommodate for higher uncertainties in load predictions, designers must increase factors of safety. The inability to confidently predict design responses has thus limited the efficiency of structures, increasing capital expenditure (CAPEX) and keeping the levelized cost of energy (LCOE) high relative to other energy generation technologies. Operating expenses (OPEX) are also inflated due to excess uncertainty in design responses. Additionally, without a reliable and efficient process with which to evaluate design responses, the ability of developers to conduct efficient design studies, especially early within the design process, is hindered. All of these factors combine to reduce investor confidence, thus increasing financing expenses.

A number of methodologies employed in the design of similar systems, such as ships and offshore oil and gas structures, are well-established and expected to provide conservative design responses for these systems [2–4]. These practices for ships and offshore structures benefit from many years of research and application on a wide variety of systems in a range of deployment environments. WEC design guidelines and standards (see, e.g., [5]) take advantage of this existing knowledge and currently rely heavily on those methods developed for ships and offshore structures. However, WECs differ from ships and other offshore structures in that they must be designed to exhibit resonance in the dominant ocean waves. Unlike a ship or an oil platform, both of which should generally be designed to respond as little as possible in waves, a WEC, in order to fulfill its purpose of energy absorption, should respond significantly in waves. To accomplish this, designers

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generally aim to place device resonance(s) within the frequency band of encountered waves. The inherently resonant behavior of WECs represents a substantial divergence from typical offshore system design. Thus, ship and offshore platform design practices can likely be applied to WECs, however, some changes may be necessary to account for the unique characteristics of WECs. To begin assessing the applicability of existing design response analysis methods to WECs, a case-study has been conducted on a simplified device.

1.1. Background

A number of relevant standards, published guidelines, and studies considering the design of WECs are currently available. Within the applicable standards, a common set of different methods are offered for obtaining long-term responses. The most rigorous, and consequently onerous, approach is a full long-term analysis. This approach produces a statistical distribution of the expect long-term response by integrating the contribution of many short-term response distributions from a range of sea states. In this process, one must assume a relevant sea state coherence interval (i.e., the length of time which a sea state is assumed to remain spectrally constant). If, as is often the case, a 3 h sea state coherence is assumed (see, e.g., [6]), the full long-term response distribution can be written as (see, e.g., [3,4,7])

$$\overline{F}_{X_{3hr}}(x) = \int_h \int_t \overline{F}_{X_{3hr}\|(t,h)}(x \parallel (T_e, H_s)) f_{(T_e,H_s)}(t,h) \ \ dt \ \ dh. \tag{1}$$

Here, $f_{(Te,Hs)}$ (t,h) is the occurrence probability distribution for a given sea state, which is represented here by the energy period, T_e, and significant wave height, H_s. The distribution $\overline{F}_{X_{3hr}\|(t,h)}$ is the short-term survival function for the response of interest, X, in that same given sea state. A survival function, also known as a complementary cumulative distribution function (CCDF), is given by

$$\overline{F}_X(x) = f(X > x) = 1 - F(x), \tag{2}$$

where $F(x)$ is the cumulative distribution function. This represents the probability that some random response, X, will exceed a limit of x. In the context of a WEC, one could produce survival functions for any number of responses, depending on the specific design of the device (e.g., mooring line tension, power take-off (PTO) force, or some structural bending moment). Thus, in (1), we have the probability that largest value of X in a 3 h sea state will exceed a limit of x. Expected limits on X can be obtained at will, e.g., for the 1 year, 25 year, 50 year, and 100 year returns levels, by accounting for the number of 3 h segments in the desired period.

Considering the large amount of simulation/modeling required to implement a full long-term analysis, alternative methods are also often applied. The recently published IEC TS 62600-2 gives design guidance for WECs as well as current energy converters (CECs) and tidal energy converters (TECs) [5]. Instructions for application of contour/design sea state ("extreme sea state: ESS" in TS 62600-2) and design wave ("extreme wave height: EWH" in TS 62600-2) methods are given by this standard. The NORSOK offshore structure design standard (N-003 [4]) describes a full long-term approach, a contour-based approach, and a design wave approach. DNV-RP-C205, which is targeted at offshore structures, gives instructions for implementing a contour-based, design sea state, and design wave approaches for long-term response prediction [3].

A contour approach uses a joint probability distribution (typically of wave height and spectral period) to define return contours. For a desired return period, e.g., 50 years, one can search along the corresponding contour by simulating/modeling a device response in the appropriate sea states. The largest response along that contour is taken to be design response. Correction factors are often applied to account for some of the assumptions included in this method. This can be accomplished by selecting a high percentile of the response distribution to represent extreme response. Within the marine industry, percentiles of 75–99% have been recommended for various structures and subsystems [3,7–10]. Alternatively, a correction factor can be applied by multiplying the expected (mean) value from the extreme distribution by some factor (Ren et al. suggests 1.3 [11]). This later approach has an advantage in that the predictions of extreme response distributions often have a large degree of variability in the tail region (see, e.g., [8,12]).

A design sea state approach is quite similar to a contour approach, however, instead of using a joint probability distribution, a simple one-dimensional distribution is utilized. Generally, a significant wave height distribution is used to find the expected significant wave height for some desired return period (e.g., $H_{s,100}$ for the 100 year return level). To obtain a spectral period (e.g., peak period, T_p or energy period, T_e), an empirical relation or local data from the deployment site is employed. The design response can then be obtained by simulating the device response in the relevant series of sea states (e.g., $H_s = H_{s,100}$, $T_{p,\min} \le T_p \le T_{p,\max}$).

A design wave approach further extends this logic by compressing the design conditions (for a given response) down to single wave series (either monochromatic or a focused wave). Based on Rayleigh distribution and a 3 h storm coherence, the monochromatic design wave height is often defined as 1.9 times the relevant significant wave height return level (e.g., $H_{100} = 1.9H_{s,100}$) [4]. Similarly to the design sea state approach, a corresponding wave period is then chosen to maximize the response within a realizable range (e.g., $\sqrt{6.5H_{100}} \le T \le \sqrt{11H_{100}}$). Alternatively, a number of methods have been proposed to construct focused design wave trains (instead of monochromatic waves) based on the conditions of interest and device response (see, e.g., [13–15]). Design wave approaches are generally only recommended for responses in which dynamic effects are known to be negligible [3,4].

To better understand the application and performance of a full long-term response analysis for a WEC, a case study has been performed. Section 2 describes the device considered in this case study and its deployment location. The numerical model used to represent this device, the environmental analysis method and short-term extreme response statistical method are also described in Section 2. Results are presented in Section 3. Section 3.1 presents analyses and results to assess the stability of this method. Section 3.2 considers the behavior of the long-term response of a number of different WEC responses. Conclusions from the study and a discussion of potential future work are presented in Section 4.

2. WEC design response case study

A diagram of the WEC analyzed in this case-study is shown in Fig. 1. The device's float is an oblate spheroid with a vertical axis of symmetry and principle radii of $r_1 = 4.5$ m and $r_2 = 1.8$ m. This float has a displaced mass of 78,000 kg, and has a resting waterline at its hemisphere. These properties are roughly representative of a single body from the Ecomerit Centipod [16]. This float is imagined to be connected to some grounded structure via a PTO, and allowed only to move in the vertical heave degree of freedom. The hydrodynamic properties of the surface float were estimated using the boundary element model (BEM) software WAMIT [17]. Fig. 2 shows the frequency response functions (FRFs) obtained from WAMIT for the vertical heave degree of freedom. The added mass and radiation