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REVIEW OF METHODS FOR MODELING WAVE ENERGY CONVERTER SURVIVAL IN EXTREME SEA STATES

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ABSTRACT

Survivability is by no means a new concept to ocean engineering; ships must remain stable and structurally intact in violent sea states; the same is true for offshore oil and gas structures. While knowledge from the ship and offshore sectors can be valuable for designing wave energy converters (WECs) for survival in rough seas, the unique scale, siting and operational characteristics of WECs pose a distinct set of engineering challenges. This paper seeks to provide a review of methods for modeling the loading and dynamic response of WECs and analogue marine structures, such as ships and offshore structures, in large nonlinear waves. We identify current knowledge gaps in our understanding of WEC survivability and provide recommendations for future research to close these gaps.

INTRODUCTION

Thus far, most WEC research and development has focused on operational performance (optimizing energy capture and conversion efficiency). The commercial viability of a WEC is equally dependent on its ability to operate, with minimal downtime for repairs, for many years. This second aspect comprises two components: reliability and survivability.

While the terms reliability and survivability are occasionally used interchangeably, the recognition of two unique definitions is essential to the function of a more systematic WEC design process. The development of standardized definitions for these terms was presented by Brown et al., in which the authors used wind turbines as a proxy to illustrate the distinction between reliability and survivability [1]. Wind turbines have relatively few survival issues, as their ability to pitch their blades into strong winds has proven to be very effective at limiting loads during storms. Conversely, reliability continues to be an issue for wind turbines, as gearbox failures from regular wear-and-tear exceed expectations. Drawing on inferences from other engineering disciplines, Brown et al. defines WEC survivability as "*the ability of a marine energy system to avoid damage, during sea states that are outside of intended operating conditions, that results in unplanned down time and the need for service.*" It is important to note from this definition that survivability pertains specifically to extreme sea states, but not other statistically infrequent events (e.g., boat strikes, rogue waves or tsunamis). This restriction is critical to utility of survivability as metric in WEC design and we therefore adhere to this definition in the following review.

Even when we restrict our focus to the survival of WECs in extreme sea states, the definition of an extreme sea state is, as it pertains to WEC survival, somewhat ambiguous. While structural loading in a device will tend to grow with wave height, the trend is also likely to possess a number of local maxima associated with certain wave period and height combinations. These local peaks could be points of resonance or simply scenarios that causes intense loading of the device. A priori knowledge of which sea states will cause the highest levels of loading in a specific WEC is not often available. WEC survival analysis must, therefore, be an iterative process, such as that shown in Figure 1. This diagram illustrates a process in which extreme sea state characterization, modeling and failure analysis are combined to assess and understand the unique survivability concerns for a particular WEC taxonomy, design and deployment site. This paper's focus is mainly restricted to the response modeling component of the WEC survival analysis process. In that interest, the remainder of this paper is organized into sections on extreme sea state characterization, response modeling, special modeling considerations and a discussion of the how WEC development could benefit from further research in the area of survival analysis.

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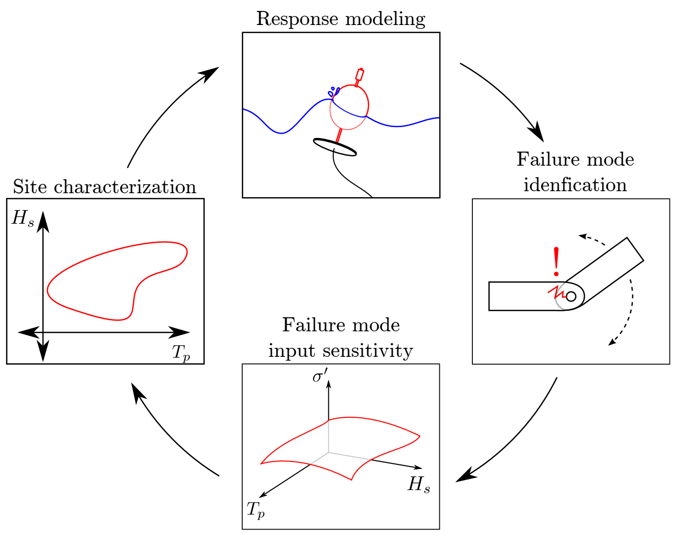

FIGURE 1. WEC survival analysis framework.

EXTREME SEA STATE CHARACTERIZATION

Extreme sea states, defined herein as a combination of extreme wind, wave and current events, represent the *input* to WEC dynamic response models. These inputs are typically determined for a WEC site from in-situ historic records that measure wind, wave and current magnitudes and directions. From these records the recurrence interval T (the return period in years that the event will occur on average), or the annual probability $P = 1/T$ of the extreme loadings can be estimated. WEC design guidance documents have yet to offer specific recommendations on the design return periods to use for extreme wind, wave and current conditions [2]. Although return periods of $T = 100$ years are common for marine structures, lower return periods can be used, if acceptable for survivability, when the design service life is less than 100 years [3]. The design service lives of WEC devices are also still somewhat speculative, but it seems unlikely that they would be more than twenty to thirty years. Therefore, it may be more economical for developers to accept more risk and design WECs for relatively less extreme conditions with $T = 50$ years.

While conditions can be estimated from historic records and statistical analysis, identifying the "most demanding" sea states on which an analysis should focus may require a relatively large systematic series of tests. In addition to wave height, a number of factors are likely to influence device response. The dependence of device response to wave length-to-height ratio (i.e., *steepness*) may be high for certain WEC taxonomies [4, 5]. Device response dependence to incoming wave angle should also be assessed. Even axisymmetric point absorbers tend to use asymmetric mooring systems; in general, the most conservative analysis can be obtained if waves are aligned with a single mooring line [6]

Insight can be gained from analyses based in both regular and irregular wave spectra. Regular wave spectra allow for more straight-forward isolation of phenomena, while irregular spectra represent a more realistic environment. If available, site-specific spectra can be used for irregular wave analyses. When no site-specific data is available, most guidelines prefer the Joint North Sea Wave Observation Project (JONSWAP) spectrum when assessing ocean structure survival [3, 7, 8]. Following the convention used by offshore oil and gas standards, a three hour duration (at full-scale) is often suggested for irregular wave survival tests [9, 4, 10, 5].

The extreme sea state conditions of the DOE Reference Model 3 device (RM3) target deployment site, which has a water depth of 50 m, were analyzed by Berg [11]. Berg employed procedures from DNV [12, 9] and the inverse FORM technique [13] to develop extreme wave, wind and current projections. Using a 100-year return period, Berg estimated that seas with a significant height of 11 m and a peak period of 17 s should be considered in survival analyses.

The use of historical records to predict extreme sea states of a given return period has recently come into question with growing evidence of climate change. Ruggiero et al. investigated the changing wave climate in the US Pacific Northwest [14]. The researchers focused on roughly 40 years of hourly wave data from two buoys. Their results showed that the average yearly significant wave height has increased steadily over that period (at a rate of 0.015 m/yr). More importantly for the application of WEC survival, Ruggiero showed that large waves are growing at a much faster rate; the average significant wave height of a five largest storms per year has grown at a rate of 0.071 m/yr. This study raises concerns about our ability to characterize extreme sea states for the purpose of WEC survivability analysis and design.

EXTREME EVENT MODELING

WECs are vulnerable to large waves for a number of reasons. As with any moored device, loads within the mooring system, including anchors, mooring lines and connection points, must be considered. An additional concern for a WEC is over-excitation and over-extension of components within the power conversion chain (PCC). Such an occurrence has the potential to create both electrical and mechanical failures. Engineers must rely upon models (numerical and physical) to identify potential vulnerabilities and assess WEC survival in extreme conditions.

Dynamic response models, that predict the motion of a WEC in waves, represent a fundamental tool in WEC design. Frequency-domain dynamic response models are often used to predict device performance and power production. These tools are, however, not well suited to analyze WEC survivability. While frequency-domain simulations can be used to model WEC response to regular waves, the highly irregular spectra that make

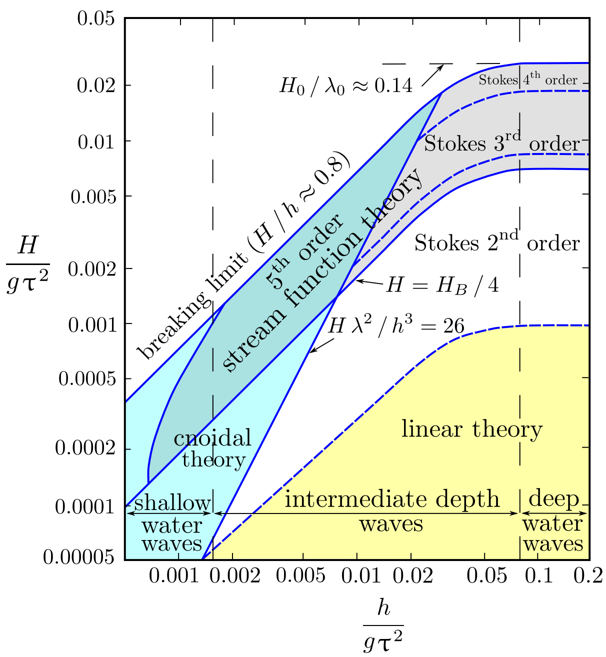

FIGURE 2. Applicability of wave formulations [15].[1]

up real sea states can only be modeled using time-domain analyses. Additionally, frequency-domain models require the use of a linear wave formulation. This constraint is mildly restrictive for an analysis focused on operational waves, but is entirely unworkable when there is a need to assess device survivability in large waves. Figure 2, originally presented by Le Méhauté [15], summarizes the applicability of various wave formulations based on wave steepness and water depth. Here, H, τ and h represent wave height, wave period and water depth respectively, while g denotes the acceleration due to gravity. Beyond their inability to handle realistic inputs (i.e., irregular nonlinear waves), frequency domain models are not capable of incorporating the nonlinear physical phenomena, such as large amplitude motions, wave breaking, viscous flow and nonlinear PCC dynamics, that come to dominate WEC loading in large nonlinear waves. The aforementioned 100-year sea state for the RM3 deployment site, for example, would require a Stokes 3rd-order wave formulation ($H/g\tau^2 \approx 0.004$ and $h/g\tau^2 \approx 0.018$).

The shortcomings of frequency-domain models necessitate more complex numerical models and physical experiments capable of more fully representing the physical systems that govern the motion of a WEC. A number of authors have presented useful summaries of numerical modeling methods applicable to WECs [16, 17, 18]. This review will examine both numerical and physical modeling methods. While a large number of methods can be recognized within this space, three main categories will be discussed here: semi-empirical and potential flow models, high-fidelity computational fluid dynamics (CFD) methods and physical model-scale testing.

Semi-Empirical and Potential Flow Methods

Semi-empirical and potential flow time-domain simulations represent the most efficient modeling method appropriate for the analysis of WECs in large waves. These models are based on ideal flow theory with the addition of factors to account for viscous effects. While semi-empirical and potential flow models can represent large nonlinear waves, they cannot handle complex free surface phenomena such as wave breaking.

Greenhow et al. presented an analysis of Salter's "duck" in extreme waves using a two-dimensional nonlinear potential flow code and experimental testing [19]. The fixed-axis device was analyzed in near shore waves that were numerically modeled to match those created in an experimental flume. Up to the point of wave breaking, the forces predicted to affect the duck by the numerical model showed fair agreement with the overall trends and magnitudes measured experimentally.

Three-dimensional nonlinear potential flow methods have seen continued interest and development in recent years [20, 21]. Sclavounos presented a novel method of calculating the forces and moments on structures within these codes that improves computational efficiency [22]. A number of studies applying these methods [23, 24] and mixed order methods [25, 26] to WECs have shown good agreement with experimental data.

A common approach in WEC design is to use a semi-empirical and potential flow model as the main driver behind the design of a WEC's mooring system [6, 27, 28]. In this approach, the need to predict localized hydrodynamic load on a device is reduced as the analysis is more focused on loads within the mooring system. The simplicity of such a model allows for straight forward execution of partial failure analyses (e.g., loading after the failure of a mooring cable).

High-Fidelity CFD Methods

With the growing availability of CFD codes capable of representing the multiphase system inherent to free surface flows, CFD has seen increasing usage in WEC survivability analyses. While these simulations are orders of magnitude more expensive to run than semi-empirical and potential flow models, they offer a much higher level of fidelity and are still quite efficient compared to physical testing. The International Towing Tank Conference (ITTC) provides a valuable set of guidelines for CFD analysis of ships that retains applicability for WECs [29].

As previously mentioned, the ability to model the response of a WEC in waves depends first and foremost on the ability to accurately model the waves of interest. Creating and propagat-

[1]Image source: "Water wave theories" by Kraaiennest is licensed under CC BY-SA 3.0

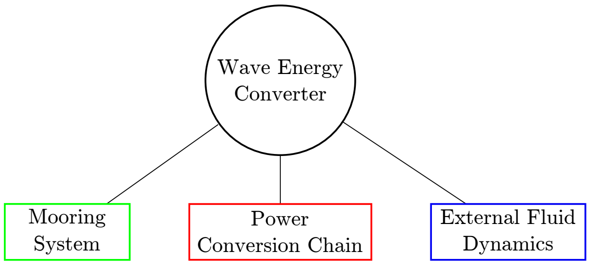

FIGURE 3. Physical systems important to WEC response modeling.

ing steep nonlinear waves is not a trivial task for CFD codes. This issue was demonstrated in a number of studies. In particular, Westphalen et al. presented results that highlight the importance of free surface formulations [30]. This study also considered the effects of boundary conditions and the use of higher-order wave formulations. Slight differences in numerical damping were shown to produce sizable discrepancies in wave propagation. Hu et al. demonstrated the effects of spatial and temporal discretization (i.e., mesh and time-step sizing) on wave propagation [31]. If a comparison of experimental data and CFD predictions for device response is planned, a separate validation to assess the accuracy of the waves in the numerical simulation can rule out a potentially large source of error.

Although analysis of the forces on fixed bodies can provide some useful information (e.g., see [32, 33]), a dynamic simulation is essential for a more complete understanding. Such a simulation must address a complex multi-physics problem, as illustrated in Figure 3. Offshore oil and gas platforms are governed by a similar system. Buchner and Bunnik modeled the response of a tension-leg platform (TLP) using a CFD code with linear springs to represent the structure's mooring lines. Numerical predictions of loads at mooring connection points in large nonlinear waves showed good agreement with experimental results. A study by Palm et al. used a framework like that shown in Figure 3 by explicitly coupling the open source code OpenFOAM with an in-house mooring system dynamics code [34]. While no experimental results were available for comparison, the study was successful in identifying a potential failure in the WEC's mooring system. A series of papers by Yu and Li showed a similar approach using the commercial code STAR-CCM+ [35, 36, 37]. A reaction plate point absorber was studied in both "locked" and "operational" PCC configurations (see subsequent Survival Configurations section for more on this topic). In the operational configuration, a spring and damper system was employed. Simple linear springs were used to model the experimental mooring system. The results from these CFD simulations showed good agreement with experimental results.

Smoothed-particle hydrodynamics (SPH) offers attractive advantages over traditional Eulerian CFD in its ability to represent complex free surface flows. Omvidar et al. compared RANS, SPH and experimental results for a two-dimensional wedge and three-dimensional cone in heave [38]. The SPH code was able to return good results for the two-dimensional case, but performed poorly in the three-dimensional case. Westphalen et al. presented another useful comparison, with analyses of a WEC comprising finite-volume, finite-element and SPH methods [39]. While the SPH code performed well in small waves, it showed increasingly poor results at larger wave heights. These studies suggest that further development is needed before SPH can be reliably used as a tool for applied research on WECs.

Physical Modeling

While theoretical advancements and increasingly affordable computing power have encouraged wide use of numerical modeling of ocean engineering systems, these analyses still rely on physical experimentation for validation. The need for physical modeling is particularly critical for WEC survival analysis, as nonlinear phenomena are important [3].

The need to properly scale different physical phenomena and values is central to experimental modeling. As is the case for surface ships, gravitational phenomena are generally more dominant than viscous effects in WEC operation; thus Froude scaling is employed. If the ratio of the characteristic lengths of a scaled model and full-scale device is given by

$$\lambda = \frac{\ell_{\text{model-scale}}}{\ell_{\text{full-scale}}},$$

scaling of the important physical parameters can be achieved using the factors shown in Table 1. Many excellent discussions on experimental scaling and dynamic similitude are available (e.g., [40, 41, 42]).

Special considerations must be given to the scaling of the various subsystems of a WEC, which are dominated by phenomena that do not follow Froude scaling (e.g., mechanical friction, stiffness, viscosity and air compressibility). Generally, the choice of a model-scale must be motivated by the phases of device development, desired type of testing and the capabilities of wave tanks. Holmes and Neilsen outlined the various phases of model testing [4, 10]. These guides suggest that WEC survival testing be executed at both small ($1/100 < \lambda < 1/25$) and medium ($1/25 < \lambda < 1/10$) scales. There are a number of documents that offer guidance on scale selection for experimental WEC modeling [41, 42, 4, 10, 5].

Returning to the example of the RM3 device discussed in the Extreme Sea State Characterization section, the challenge of conducting model-scale testing becomes quite clear. In an analysis of the RM3 device, Berg identified an extreme sea state with a significant height of 11 m and a peak period of 17 s. If testing at

TABLE 1. Relevant Froude scaling factors for WEC modeling.

Parameter	Scaling factor
Position (length)	λ
Angle	λ^0
Velocity	$\lambda^{1/2}$
Linear acceleration	λ^0
Angular acceleration	λ^{-1}
Force	λ^3
Moment	λ^4
Pressure	λ
Power	$\lambda^{7/2}$
Mass	$\lambda^{7/2}$
Time	$\lambda^{1/2}$

a scale of $\lambda = 1/15$ (as suggested by Holmes and Nielsen [4,10]) is desired, the wave tank would need to produce irregular waves with a significant height of roughly 0.75 m. Very few wave tank facilities are capable of creating waves of this magnitude.

Relatively few physical modeling studies of commercial WEC devices are reported in literature due to the business incentives experienced by WEC developers (i.e., protection of intellectual property and investor relations). Parmeggiani et al. performed a series of tests at a scale $\lambda \approx 1/50$ to assess the effectiveness of a special survival mode (see subsequent Survival Configurations section for more on this topic) [43, 44]. Forces along the device's main mooring line were measured in irregular waves representative of 10, 50 and 100-year return periods at the target deployment site. A number of wave steepnesses were assessed in each case. Whittaker et al. presented experimental data for a near-shore terminator device at a scale $\lambda = 1/40$ in large waves [45]. Foundation loading of the bottom-mounted device was assessed.

SPECIAL MODELING CONSIDERATIONS

Slamming Analysis

The term slamming is used in the ocean engineering community to refer to the rapid pressure loading caused when a body enters the water. Slamming may also occur in steep and/or breaking waves. The very small time-scales (on the order of microseconds [8]) and unique physics involved necessitate analyses specifically targeted towards slamming.

A large number of experimental analysis of water-entry slamming have been carried out with canonical bodies such as two-dimensional wedges, cones, cylinders and spheres (e.g., [46, 47]). These studies have supplied engineers with a wealth of empirical data on slamming events from which to develop numerical models. The first of these methods were developed by von Karman [48] and Wagner [49] to analyze seaplane floats. The need to analyze ship slamming events has garnered many improvements to these and other methods (e.g., [50, 51]). More recently, computational power has allowed researchers to apply CFD codes to slamming analysis problems [52, 53, 54]. These codes, which often employ mixed fidelity methods to capture near and far-field phenomena (e.g., [52]), have shown very promising results.

A group of researchers at Ghent University conducted slamming analyses of a composite WEC point absorber [55, 56]. Large-scale ($\lambda = 1/3$) physical drop tests were performed in conjunction with finite element analysis (FEA) modeling to determine loading within the structure. CFD simulations of the slamming event were also conducted. As the use of composite structures in this application is somewhat novel, tests were specifically designed to assess the effects of reduced structural rigidity. For the device tested, the increased ductility of the composite structure reduced pressure loads by roughly 50%. The results from this study's high-fidelity models showed major discrepancies with values determined using semi-empirical methods suggested by DNV [9].

Survival Configurations

As waves get larger, a WEC's primary goal must transition from efficient energy production to survival. The nature of this transition, whether it is a discrete line or a more gradual change, and in what wave condition it occurs, is likely to be highly device-dependent. Figure 4 offers an idealized example of WEC's survival behavior in various combinations of significant wave height, H_s, and peak period, T_p. Below the curve, the device can operate normally, with its main goal being energy production. Above the curve, the device must operate in a survival mode to avoid damage. The trend shown in Figure 4 is meant to be representative of a typical WEC, to which steep short-crested waves are likely to pose a larger threat. A method to account for this behavior in cost analyses is suggested by Brown et al. [1].

A number of distinct survival modes and strategies have been developed for WECs. In some devices, a passive behavior can be used to protect the device in large waves. The Pelamis device's design allows it to effectively detune in waves of a height larger than the diameter of its cylinders [57]. In Stallard et al., a study was performed to investigate tailoring the above-water geometry of a point absorber in a way that allows for small changes in draft to result in large changes in device response [58]. The study achieved a 50% reduction in device response with a need for only a 10% change in mass. Terminator devices often change their angle to incoming waves or increase

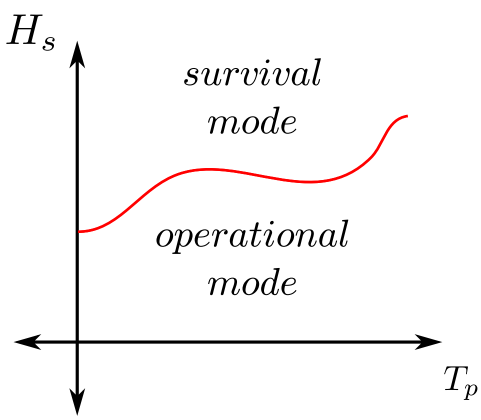

FIGURE 4. Idealized contour of WEC survival and operational modes.

their draft to reduce energy absorption, and therefore loading, in large waves [34, 43, 44, 59]. In other devices, the PCC can be "locked" to prevent motion and problems with component end stops [45, 6, 35]. Some research has also been focused on applying the concept of life extending control (LEC), in which control algorithms are used to alter a WEC's PCC performance to avoid damage [60]. Such efforts have the potential to interface well with ongoing work to improve WEC energy absorption through control (e.g., [61]).

CONCLUSION

A robust WEC survival design process, such as that illustrated in Figure 1, requires a set modeling tools, with a range of fidelities. Low-fidelity models are needed to identify a WEC's most vulnerable failure modes and high-fidelity models are needed for further analysis of those scenarios. While a number of useful modeling methods are available, well-targeted validation work has the potential to better determine which of these methods is best suited to each stage of a WEC survival analysis cycle.

Along with the need for effective models comes a need for a carefully considered and purposeful framework in which they can be used. Without perfect knowledge of which waves will constitute a threat to a specific WEC, a systematic approach must be employed to the survival aspect of WEC design. Additional consideration and experience in this area would greatly benefit future development efforts.

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