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A high-fidelity wave-to-wire simulation platform for wave energy converters: Coupled numerical wave tank and power take-off models

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HIGHLIGHTS

- A novel high-fidelity simulation platform is presented coupling CFD and a PTO model.
- CFD-based approaches are reinforced for applications where high-fidelity is vital.
- Significant overestimation is observed for excessively simplified PTO models.
- Minor inaccuracies in a conversion stage can significantly affect the power estimate.

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ABSTRACT

Performing rigorous technical and commercial assessment of wave energy converters (WECs) numerically, before engaging in expensive wave tank and open ocean tests, is vital for the economically successful development of prototypes. To that end, this paper presents a high-fidelity wave-to-wire simulation platform (the *HiFiWEC*), where a Computational Fluid Dynamics (CFD)-based numerical wave tank is coupled to a high-fidelity power take-off (PTO) model, which enables assessment of WEC performance with greater accuracy than with previous wave-to-wire approaches. A test case, simulating the performance of a heaving point absorber type WEC in realistic conditions, is presented and compared against traditional lower fidelity modelling methods. The WEC response is evaluated with a number of different approaches, including different techniques to model hydrodynamic wave-structure interactions and the power take-off system, and the benefits of the *HiFiWEC* are highlighted. The results highlight that excessive simplifications in the modelling of the PTO system can lead to significant overestimation in generated energy output, with relative deviations (ϵ) of up to 150% compared to the *HiFiWEC*. In addition, uncertainty in viscous drag parameters added to hydrodynamic models based on boundary element method solvers, reinforce the necessity of CFD-based models for applications where high-fidelity is essential. Finally, it is demonstrated that minor/insignificant inaccuracies in the hydrodynamic model (ϵ = 0.5%) can result in significant differences in the estimation of the final energy generation (ϵ = 7%), highlighting the need for a coupled high-fidelity platform.

1. Introduction

Clean energy technologies are fundamental to the development of a low-carbon environment, to mitigate the effects of human-induced climate change. Currently, about 20% of mankind's energy consumption is supplied by renewable energy sources, such as hydropower, wind or solar energy [1]. However, in the coming decades, a much larger share of the energy supply must be provided by renewables, requiring the contribution of additional renewable energy sources to the mix. Ocean waves present a tremendous untapped energy resource, about 32,000 TWh/year according to [2], which could make a substantial contribution to the future supply of clean energy. However, the ocean is an extremely harsh environment, making the extraction of wave energy complex and expensive [3]. Due to this complexity, over 200 different prototypes have been suggested to harvest wave energy [4], but none have yet demonstrated commercial viability.

The development of wave energy converters (WECs) is a slow, risky and expensive process. The evolution, from the initial idea through to the final commercially competitive device, requires a number of distinct development stages. Assessing the commercial and economical ability of the WEC, at different stages of its development path, can be quantified using technology readiness levels (TRLs) and technology

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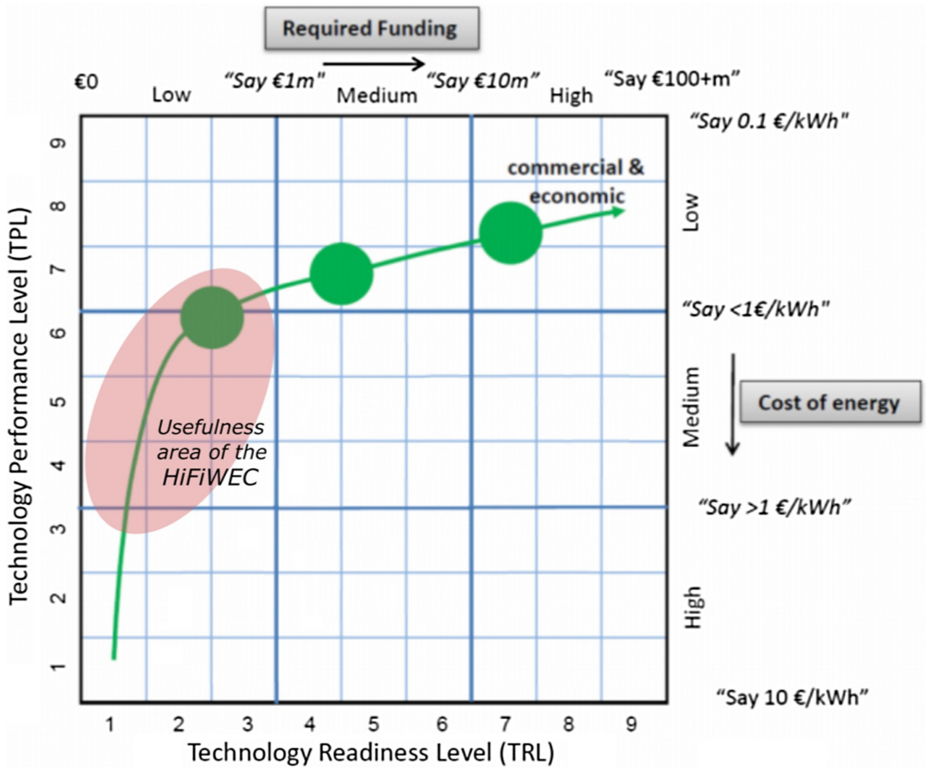

Fig. 1. TRL and TPL matrix with the ideal development trajectory and the applicability area of the *HiFiWEC*, adapted from [5].

performance levels (TPLs), respectively, as described in [5]. The ideal development trajectory, suggested in [5], delays the expensive prototype demonstration at higher TRLs, until reaching a high level of confidence on the concept, by first traversing the TPL scale at lower, less costly, TRLs, as illustrated in Fig. 1.

To evaluate the performance of a WEC at low TRLs, simulation models are required with increasing accuracy for increasing TPLs: the higher the TPL, the higher the level of modelling accuracy is needed to realistically assess the increase in WEC performance, and correspondingly the higher the accepted computational cost for the simulations. Therefore, to rigorously assess and optimise a WEC at low TRLs, before undertaking the critically expensive demonstration stages at higher TRLs, high-fidelity simulation models are essential to gain confidence in the expected WEC performance. These high-fidelity models must be able to evaluate the holistic performance of WECs, including the wave-structure interaction (WSI) and the power take-off (PTO) drivetrain. Such holistic models are typically termed wave-to-wire (W2W) models and are reviewed in [6].

Separate high-fidelity models for hydrodynamic WSIs and different PTO systems have been suggested in the literature. Computational Fluid Dynamics (CFD) are used to solve WSIs for various WEC types, such as point absorbers [7,8], oscillating wave surge converters [9,10] or oscillating water columns [11,12] (see a full review in [13]). However, W2W models that incorporate CFD to model hydrodynamic WSIs always use excessively simplified PTO representations, i.e. linear spring-damper systems [13], resulting in highly unbalanced W2W models with an unjustifiable computational cost.

Similarly, high-fidelity models for different PTO systems have been suggested in the literature. These high-fidelity PTO models are, in general, coupled to relatively simple hydrodynamic models, mostly using a linear potential flow model based on Cummins' equation, which is sometimes extended with a quadratic viscous model, in the most complicated cases. Examples of W2W models with relatively high-fidelity PTO models can be found in the literature for different PTO system, e.g. air turbines [14–18], hydraulic PTO systems [19–26], mechanical transmission systems coupled to rotational electric generators [27,28] or linear generators [29–31] (see a full review of W2W models in [6]).

However, to the authors' knowledge, no published model offers the possibility to evaluate the performance of WECs in a holistic numerical test bed, including sufficient fidelity of both the hydrodynamic and PTO models simultaneously. The only parsimonious model that evaluates the holistic performance of a WEC is presented in [32] (referred to as the *NLBEMW2W* model in the following sections), for which the hydrodynamic WSIs are solved via a partially nonlinear model based on boundary element method (BEM) codes, such as NEMOH [33].

To fill this gap, the present paper presents a novel holistic high-fidelity W2W simulation platform, the *HiFiWEC*, which is the first attempt to couple a high-fidelity CFD-based numerical wave tank (CNWT) to a high-fidelity PTO model. Hence, the *HiFiWEC* offers a high-fidelity simulation model for medium-high TPLs and low-medium TRLs, as shown in Fig. 1.

The *HiFiWEC* can be particularly useful:

- as a benchmark to validate lower fidelity or computationally more efficient mathematical models [34],
- for system identification purposes, identifying the viscous drag coefficient [35] or representative/parametric models [36,37] under realistic operational conditions,
- to evaluate the efficacy of control strategies in realistic conditions [38,39].

While these applications would traditionally have required physical wave tank experiments, the *HiFiWEC* offers some advantages compared to its physical counterpart. The *HiFiWEC* can eliminate undesired influences of measurement equipment and the test environment, e.g. the unrepeatability of experiments [40], reflections from tank walls [41] and friction from device restraints at small scale [42], as well as to evaluate devices at full scale [10]. Also, the difficulty in evaluating the performance of full-scale PTO systems and their impact on

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