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Optimization at different time scales for the design and management of an oscillating water column system

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ABSTRACT

This research used an optimization method to highlight the importance of time scales in the design of a bottom-fixed OWC (oscillating water column). The different time scales studied were a sea state, a season, and a year. For the last two scales, a stochastic formulation was used to take into account the random nature of the wave climate in the time interval considered. This paper also describes a general methodology for the study of the non-stationary performance of an OWC device during its useful life, which was applied to obtain the available pneumatic power. It entailed simulations of the wave climate and the corresponding OWC-related performance magnitude, which reproduced the intra-annual and interannual climate variability at the site. This methodology was used to analyze the management-related random variables for three optimal OWC configurations on different time scales. The results of this study show that OWC performance can be enhanced by designing systems whose configuration can be adapted to successive sea states. This opens a line of research with promising technological implications that is well worth exploring in greater depth.

1. Introduction

The generation of energy from the seas and oceans, particularly that derived from wind-driven waves (i.e. wave energy), has developed rapidly over the years [1,2]. Since the first patent was filed in France in 1799 (see Ref. [3]), a wide variety of WECs (wave energy converters) [4,5] have been designed. Of these devices, the OWC (oscillating water column) has been the focus of much research. In fact, it was one of the first to be built as a full-size prototype [4].

Generally speaking, the design of an OWC system involves the calculation of the following: (1) available wave power, P_w, based on wave characteristics; (2) time-averaged power production of the turbine, $\overline{P}_{avai}$, depending on the incident waves, system geometry, turbine characteristics, and air compressibility in the air chamber; (3) time-averaged power output of the turbine, $\overline{P}_t$, based on $\overline{P}_{avai}$ and the efficiency curve of the turbine; (4) net electrical power $\overline{P}_e$ which depends on the value of $\overline{P}_t$ and the mechanical and electrical losses of the system.

Until now, various research studies have focused on the optimal design of high-performance OWC devices. López et al. [6] implemented a numerical model to study the performance of a fixed OWC, depending on wave conditions and the damping exerted by the turbine. The numerical model was validated using the results from physical model tests, and an excellent agreement was obtained between the two models. This permitted the authors to identify the optimal characteristics of a turbine capable of maximizing the capture factor for a given set of wave conditions. Subsequently, López et al. [7,8] experimentally analyzed the influence of the tidal level on the performance of a fixed OWC, and found that the most important factor in OWC performance was turbine damping.

Falcão and Rodrigues [9] developed a stochastic method to calculate the time-averaged power output of an OWC wave energy device equipped with a Wells turbine. Their model was applied to a real wave climate scenario. The energy production of the plant was optimized by controlling the rotational speed of the turbine. Falcão [10] implemented this model for three wave climate scenarios by varying the turbine diameter. He then compared the results of using two different criteria, namely the maximum annual electrical energy production and the maximum annual profit.

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Martins-Rivas and Mei [11] specified the characteristics of a maximally efficient turbine in a fixed OWC device without limiting its rotational speed, for the whole range of frequencies. Their study considered different values of the relative radius, relative submergence and air volume inside the chamber. In some of the cases, a 100% efficiency was reached at two different frequencies. Lovas et al. [12] applied this same methodology to two OWCs at two cornered coasts and analyzed the influence of the geometry and incident wave angle. It was assumed that the turbine parameters could only have two values for the whole range of frequencies considered.

Gomes et al. [13] used the stochastic model in Falcão and Rodrigues [9] to optimize the geometry of a floating OWC device and thus maximize the annual average power available to the turbine. Falcão et al. [14] specified the values of the tube geometry and turbine characteristics of a floating OWC that maximized wave energy absorption for regular and irregular waves. They also analyzed the influence of the wave period and air chamber volume on the optimization results.

Quite frequently, research studies that obtain an optimal annual geometry for real-life scenarios calculate energy production based on a set of sea states that are representative of the wave climate at the location. However, certain studies highlight the impact of the intra-annual variability of wave energy on the electrical power thus generated. Carballo and Iglesias [15] developed a methodology that determined the performance of an arbitrary WEC based on the calculation of the mean monthly power available at the WEC site, and which was applied to a real-life wave climate scenario on the northwest coast of Spain. It was subsequently used to assess the performance of different WECs at an offshore and nearshore location on the north coast of Galicia (NW Spain) [16]. Both studies show the importance of considering the intra-annual variability of the wave climate where the WEC is to be installed.

The temporal variability of the wave climate should be considered in the design of such devices, but it should also be taken into account in order to simulate time series that permit the prediction of the future performance of WECs and optimally manage their operation. Mackay et al. [17] modeled the interannual variability of the mean power by using the NAO (North Atlantic Oscillating) climate index to predict the performance of a WEC on the north coast of Scotland.

This paper describes the optimization of a bottom-fixed OWC device at different time scales. This optimization takes into account the random nature of the wave climate during the time interval of the study. Also presented is a statistical analysis of management-related variables that measure the performance of the OWC device during its useful life. These variables are sampled from simulations that reproduce the non-stationary variability of the wave climate as well as the available pneumatic power.

The bottom-fixed OWC device in this study is smaller than other similar devices with a transversal area in the range of 80–250 m^2. Located at medium or shallow depths, it can perform well in seas with low-energy waves, which are very frequent at certain times of the year (seasonal cycle). This is typical of the Gulf of Cadiz, which is located southwest of the Iberian Peninsula.

The main research objective was to highlight the importance of time scales in the optimization of an OWC under random wave action. As an example, the available pneumatic power for the turbine was selected as the objective function, and the submergence and rotational speed of the turbine were chosen as decision variables. However, by suitably adjusting the variables, this methodology can be applied to any other magnitude that depends on wave climate, such as the cost-benefit function. The time scales considered were seasonal and annual. The constraints to be satisfied were the following: (i) geometric, imposed by the depth at which the system is located; (ii) aerodynamic, related to the maximum speed of the turbine; (iii) operational, linked to the operational thresholds of the device. Because of the random nature of the wave climate, the problem was addressed in the same way as a stochastic optimization that provides statistically optimal values.

Based on the results of the stochastic optimization, two OWC configurations were considered. This study calculated their corresponding distribution functions of the available pneumatic power for the turbine in the sea state. These results were compared with those obtained for an ideal device capable of adapting itself to the optimal geometry of each sea state (deterministic optimization).

For the optimal configurations, the study analyzed certain variables related to the non-stationary performance of the device, which were crucial for the effective management of the OWC system. For this purpose, the time series of the available pneumatic power were simulated for a large number of wave climate realizations during the system's useful life, based on significant wave height and peak period.

These time signals were obtained with the methodology proposed by Solari and Van Gelder [18] for the simulation of multivariate series using non-stationary mixture distributions, which contemplate the intra-annual and interannual variability in Solari and Losada [19]. *Intra-annual variability* refers to monthly and seasonal variations, whereas *interannual variability* refers to cycles with variation intervals longer than or equal to one year.

This paper is divided into six sections. Section 2 describes the OWC device as well as the time variability and random nature of the forcing agent and the pneumatic power. Section 3 outlines the optimization method for the different time scales as well as the methodology used to study the variables related to the management and exploitation of the OWC device. In Section 4, this methodology is applied to the OWC site on the Andalusian Atlantic coast, and the results are presented. Section 5 discusses the results, and Section 6 lists the conclusions that can be derived from this research.

2. Formulation of the problem

2.1. Description and operational constraints of the OWC system

The OWC device in this study is located on the inner continental shelf in a zone of constant depth h near the coastline. It is

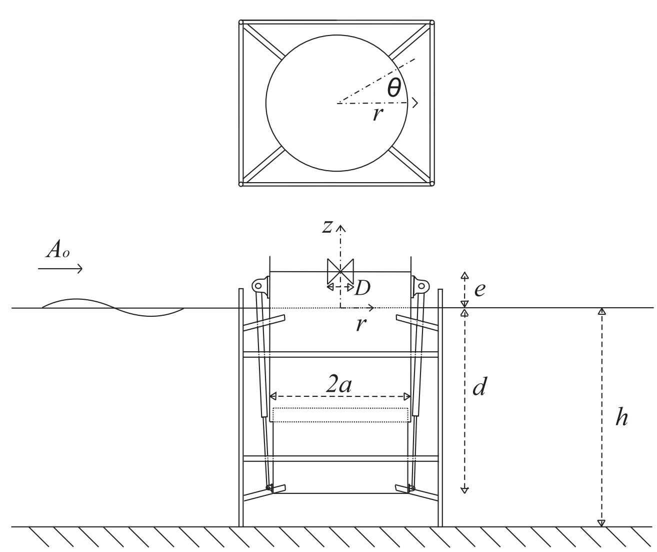

Fig. 1. Diagram of the possible design of the OWC system.