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Investigation on the energy absorption performance of a fixed-bottom pressure-differential wave energy converter

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ABSTRACT

In this article, we investigate the energy absorption performance of a fixed-bottom pressure-differential wave energy converter. Two versions of the technology are considered: one has the moving surfaces on the bottom of the air chambers whereas the other has the moving surfaces on the top. We developed numerical models in the frequency domain, thereby enabling the power absorption of the two versions of the device to be assessed. It is observed that the moving surfaces on the top allow for easier tuning of the natural period of the system. Taking into account stroke limitations, the design is optimized. Results indicate that the pressure-differential wave energy converter is a highly efficient technology both with respect to energy absorption and selected economic performance indicators.

1. Introduction

Ocean waves are a largely untapped natural renewable energy resource [1]. Since the early 1980s, hundreds of wave energy converters (WECs) have been studied and developed. Review of technologies can be found in [2] or [3]. Several full-scale prototypes have been tested at sea, however WECs have still not reached the commercial stage. This is mainly because of their high cost of energy in comparison with other renewable energy technologies such as wind or solar photovoltaics [4–6].

The cost of wave energy may decrease in the long term with industrialization and mass production of successful WEC prototypes. However, it is uncertain that a sufficient level of cost reduction can be achieved with WEC technologies based on well-known working principles (see for example [3] for a review of working principles of wave energy converters). That is why it is crucial to carry on basic research of new wave energy concepts and components as it may lead to a breakthrough in energy and economic performance. Examples of potential revolutionary technologies include flexible WECs such as the Anaconda WEC [7] or the S3 WEC [8]; passively phase-controlled WECs such as the CorPower WEC [9]; or WECs with variable geometry such as the National Renewable Energy Laboratory's (NREL's) oscillating wave energy converter [10].

Another example is the M3 flexible WEC [11], known as a pressure-differential device. It takes advantage of the spatially varying pressure differentials in the wave field to drive a fluid flow. The working principle of the M3 WEC is described in [12]:

> (It) consists of two deformable air chambers separated by a distance on the order of half a wavelength. The chambers are connected by a pipe with an internal bidirectional turbine. The device is fully submerged and fixed near the sea floor. Due to dynamic wave pressure, one air chamber compresses while the other expands forcing air through the turbine. As the wave pressure progresses, the pressure differential switches signs, reversing the direction of the air flow.

Fig. 1 shows a picture of a scale prototype of the M3 WEC that was deployed and tested offshore the coast of Oregon in September 2014.

In [12], the separating distance and orientation of the device was optimized to maximize the excitation pressure on the device assuming diffraction is negligible. It was found that for a nondirectional spectrum, the optimal distance between the chambers is close to half the wavelength of the spectrum peak frequency.

The WEC itself was not modeled in [12]. To our knowledge, there are no other publicly available studies that cover the energy performance of pressure-differential WECs (such as the M3

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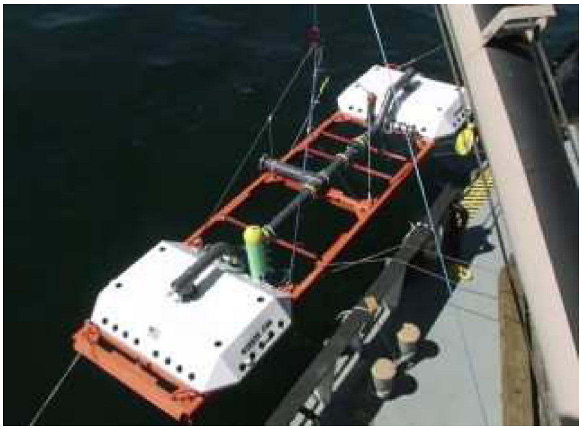

Fig. 1. The scale prototype of the M3 WEC during its deployment offshore the coast of Oregon in September 2014. Photo courtesy of M3 Wave LLC.

WEC). Thus, the energy performance of fixed-bottom pressure-differential wave energy converters is an open question, and is therefore the motivation for this study.

The rest of the paper is organized as follows. In Section 2, numerical models of two versions of the pressure-differential WECs are presented. A frequency domain approach was used. One version has the moving surfaces on the bottom of the air chambers whereas the other version has the moving surfaces on the top. Fundamental differences between the two versions are discussed. In Section 3, we provide comparisons of numerical results for energy performance. The most promising design is further investigated and compared to other WEC technologies for energy and economic performance.

2. Numerical model

2.1. Ocean waves model and wave resource

In this study, ocean waves were modeled by unidirectional irregular waves. Irregular waves are a more realistic model for real ocean waves than regular waves. Only unidirectional waves were considered because the pressure-differential WEC device is designed for small water depths where directional spreading is expected to be negligible thanks to refraction.

In this work, we considered the wave resource for a site located on the west coast of France. The scatter diagram for the wave resource at this site is shown in Fig. 2, which was obtained from actual measurements of the wave elevation [13]. However, only the joint probability distributions for the significant height, H_S, and the spectrum peak period, T_P, are available. The measured sea spectra were not retained. Therefore, it is necessary to assume a spectral shape for the wave spectrum. The JONSWAP spectrum was used in this study with a frequency spreading parameter $\gamma = 3.3$.

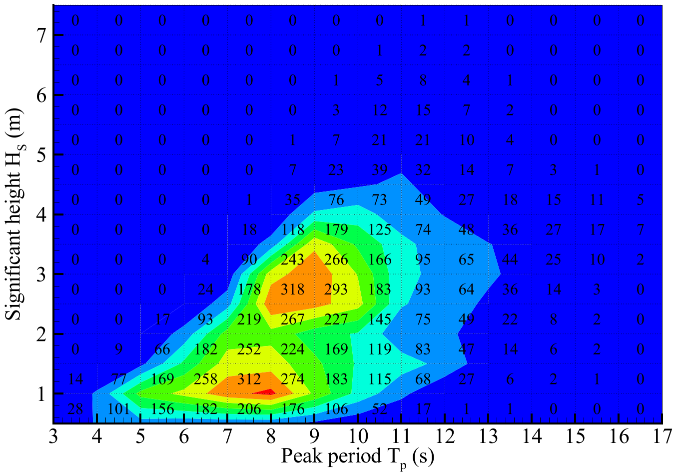

Fig. 2. Measured wave scatter diagram offshore Yeu island on the west coast of France (GPS coordinates 046°40,000′ N–02°25,000′ N).

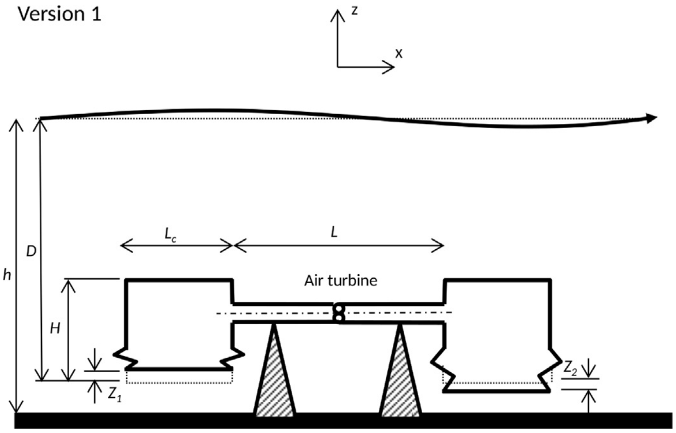

Fig. 3. Sketch of version 1 of the pressure-differential wave energy device with moving surfaces on the bottom.

The mean water depth is 47 m at the point where the wave resource was measured. The targeted deployment water depth of the pressure-differential WEC is shallower. The effect of water depth on the wave spectrum and wave resource must be taken into account. The waves were assumed to propagate into shallow water according to linear refraction. Because of bottom friction and wave breaking, the wave resource is expected to be less near-shore than offshore. In [14], it was shown that the gross wave resource from a 50-m water depth site to a 10-m water depth site is reduced by 20% to 44%. At first, we assumed a constant energy loss of $\epsilon = 30\%$ for each and every wave component in the wave spectrum. Thus, the following ad-hoc near-shore wave spectrum S_h was used:

$$S_h(f) = \frac{1-\epsilon}{\tanh(kh) + \frac{kh}{\cosh(kh)}} S_\infty(f) \quad (1)$$

where f is the frequency, h is the water depth, k is the wavelength, and S_∞ is the well-known JONSWAP spectrum. The factor $1-\epsilon$ accounts for the fraction ϵ of the wave energy that is dissipated. The factor $\frac{1}{\tanh(kh)+\frac{kh}{\cosh(kh)}}$ takes into account the wave amplitude modulation caused by shoaling.

2.2. Version 1 of the pressure-differential WEC: moving surfaces on the bottom of the air chambers

Fig. 3 shows a sketch of the pressure-differential wave energy device. This version is inspired by the M3 WEC, which has the deformable membranes on the bottom of the air chambers. For simplicity, the supporting frame shown in Fig. 1 was excluded in the numerical model. Note that there may be other significant and important differences both in geometry and configuration between the studied device and the system that we used as a source of inspiration, thus also the performance may differ.

The studied device consists of a structure standing on the sea bottom and two identical air chambers. The air chambers are connected with a pipe that allows air to be exchanged between the chambers. The power take-off (PTO) is an air turbine that converts the kinetic energy of the air flow in the pipe into mechanical rotational energy. Then, the mechanical rotational energy can be converted into electricity using a generator. The waves are propagating from left to right.