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Feasibility study of the three-tether axisymmetric wave energy converter

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ABSTRACT

There are numerous designs and concepts that have been offered to extract energy from ocean waves. A heaving buoy is distinguished as the most popular device which predominantly harnesses energy from the vertical motion in waves. One such device is the bottom-referenced submerged heaving buoy represented by the Carnegie Clean Energy CETO system. The total power absorption of this converter can be increased by replacing the single-tether power take-off system by a three-tether mooring configuration thereby making motion controllable in heave and surge. The current paper provides a comparative performance analysis of the generic submerged heaving buoy connected to one tether and the three-tether converter in terms of the buoy motion, and design of the power take-off and mooring systems. This is accompanied by a techno-economic analysis of two converters.

1. Introduction

Along with wind and solar power, ocean waves are a huge source of sustainable energy that still remain unexploited for electricity generation. Despite more than 40 years of intensive research and more than 200 wave energy converter (WEC) designs, there is no definitive answer to the question of what working principle is more suitable for shallow or deep water, or what scale of the device is more economically viable. As a result, none of the existing designs has reached the commercial-scale stage, still remaining at the proof-of-concept development phase. Therefore, researchers and engineers continue to look for new solutions in order to make wave power competitive with other sources of renewable energy.

Along with various sizes and shapes, WECs differ in operation principle including the mode of motion utilised to convert wave power. Thus, heave, surge, and pitch of the structure are the main modes usually used in practice. Depending on the converter geometry and its location relative to the mean water surface, the oscillatory motion of the WEC in different modes radiates different types of waves leading to the different power absorption levels (Pecher and Kofoed, 2017). Thus, systems that combine several modes of motions have better hydrodynamic performance and the structure placed in water can be used more efficiently (Falnes, 2002). As an example, bottom-referenced heaving buoys similar to the CETO system (Carnegie Wave Energy Limited, 2015) are designed to absorb power from the vertical motion in waves (see Fig. 1a). While heave has a major contribution to the power absorption due to a flexible tether connection between the buoy hull, the power take-off system, and the seabed, the structure can experience movement in all degrees of freedom. In order to increase the efficiency of such WECs, it has been suggested (Srokosz, 1979) to use a three-cable mooring configuration (see Fig. 1b) which allows to control motion of the buoy in both heave and surge, and to some extend in pitch. Interestingly, that an added degree of freedom (e.g. surge) can significantly improve the performance of fully submerged quasi-point absorbers, while the efficiency of their floating counterparts will increase only in a limited range of wave periods (Sergiienko et al., 2017).

The concept of the three-tether WEC was introduced by Srokosz (1979), where a submerged spherical buoy was attached to three cables that were equally spaced around the buoy and each cable was connected to an individual power-take off machinery. The study was conducted in the frequency domain and demonstrated up to a threefold increase in power production as compared to the same buoy connected to only one cable. Later, the three-tether converter with a floating cylindrical buoy was used as a prototype for the control system design (Lattanzio and Scruggs, 2011; Scruggs et al., 2013). Further analysis has been focused on the design features of the three-tether WEC with an objective to identify the optimal arrangement of tethers which can provide the maximum power output of the converter (Sergiienko et al., 2016a). In addition, there is an interest in developing wave energy arrays consisting of multi-tether buoys due to the benefit of shared moorings (Wu et al., 2016; Arbònes et al., 2016).

At the initial stage of any prototype development, the main research

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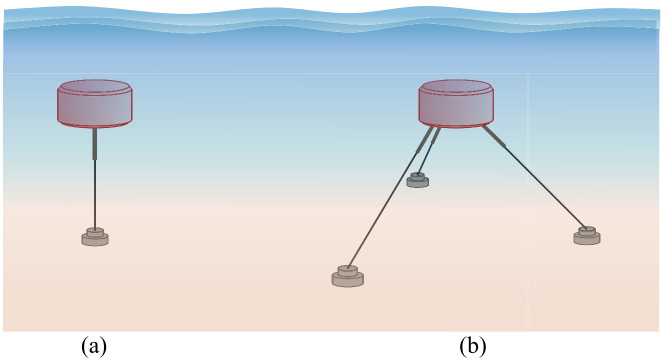

Fig. 1. Different power take-off configurations for the submerged WECs: (a) a generic heaving buoy connected to one tether; (b) a three-tether system.

focus is given to the technical side of the problem: efficiency of the WEC under regular waves with idealised control, a dependence of the device performance on the geometry and constraints, etc. However, when it comes to the commercialisation of a particular converter, other factors become significant for investors. Thus, the system with the best hydrodynamic performance does not necessarily guarantee the cheapest electricity production (Pecher and Kofoed, 2017). Therefore, recently, considerable attention has been given to the techno-economic assessments of the WEC development. Since only a few devices have been built in full-scale and undertaken in-ocean testing, the amount of information on levelised costs or capital/operational expenditures of WECs is limited. Therefore, a number of indirect cost-related criteria has been developed for converters at low technology readiness level (Babarit et al., 2011, 2012). Regarding the three-tether WEC, the preliminarily results of its performance in irregular waves have been presented in Sergiienko et al., (2016b) including the estimation of energy delivery and other indirect techno-economic indices.

The current paper demonstrates a feasibility study of the three-tether wave energy converter with one shape of the buoy hull. Descriptions of the system and modelling routine are specified in Sections 2 and 3 respectively. The performance of the WEC and expected power output are presented in the form of comparative analysis between the single-tether and three-tether WECs in Section 4. Uncertainties associated with the modelling assumptions are quantified in Sections 5 and 6. Finally, the techno-economic analysis of the three-tether WEC is presented in Section 7.

2. Description of the system

2.1. Buoy

Currently, there is no physical prototype for a three-tether wave energy converter which can be used for analysis in the current study. Therefore, it has been decided to utilise a generic shape, namely a vertical cylinder, whose hydrodynamic behaviour has been thoroughly studied (Yeung, 1981; Jiang et al., 2014). In practice, corners of the buoy should be rounded to reduce drag and viscous losses (Pecher and Kofoed, 2017), but for the numerical modelling in this study only the aspect ratio of the device is important. The geometrical dimensions of the buoy hull are selected to be similar to the CETO-5 system as specified in Table 1.

2.2. Power take-off configuration

In the current study it is assumed that each tether is connected to an individual power take-off (PTO) mechanism, which can be implemented as an electric generator (Scruggs et al., 2013) or a hydraulic circuit (Ding et al., 2016). For the three-tether WEC it is possible to place the PTO system inside the buoy hull, where all three hydraulic cylinders drive the same power generator (Hansen et al., 2011). The behaviour of the hydraulic system is usually described by the Coulomb damping force (Babarit et al., 2011). However, in order to exclude uncertainties associated with a specific PTO design, it is presumed that the machinery force has linear spring and damper effects proportional to the tether extension and the rate of change of the tether extension, respectively.

Table 1
Parameters of the WEC.

Parameter	Value
Shape	vertical cylinder
Radius of the cylinder, a	5.5 m
Height of the cylinder, h_c	5.5 m
Water depth	50 m
Submersion (top of the buoy)[a]	3.75 m
Submergence depth, d_s (centre of the buoy)	6.50 m
Volume[a], V	524 m^3
Surface area[a]	380 m^2
Mass of the buoy, m_b	268 t
Displaced mass of fluid[a], m_w	537 t
Stroke length, $\Delta l_{max} - \Delta l_{min}$	6 (±3) m
Tether inclination angle from the vertical, α	44°
Initial tether length[a], l_0	56.6 m
Pretension force in each tether[a]	1.2 MN

[a] not independent parameters.

2.3. Sea site

There is a range of sea site locations that can be used to assess the overall performance of the WECs including Australia (Australian Wave Energy Atlas, 2016), Europe (Babarit et al., 2011) or the USA. However, Yeu island located in France has been extensively used as a benchmark site for the comparison of various WEC prototypes (Babarit et al., 2012; de Andres et al., 2016) and therefore will be considered in this study. The wave data statistics and parameters of the site are specified in Fig. 2.

Location:	46°40′00.0″N, 2°25′00.0″W
Water depth:	48 m
Mean wave power:	25.5 kW/m (Pierson-Moskowitz)
Type of data:	Real sea measurement (as cited in (Babarit et al., 2012)).

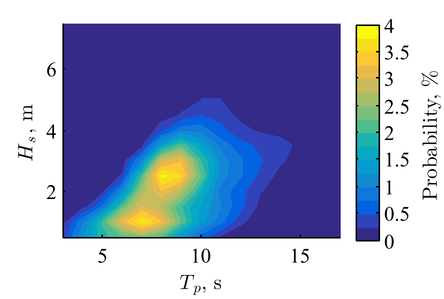

Fig. 2. Wave data statistics for France/Yeu island site. Source of data is (Babarit et al., 2012).

3. Equation of motion

The wave-to-wire model employed in this study is based on linear wave theory, assuming small motion amplitudes of the buoy as compared to the length of the mooring lines (tethers). The only second-order hydrodynamic effect included in the model is a viscous drag force which is proportional to the square of the body velocity relative to the fluid.

3.1. Kinematics

A schematic of a three-tether WEC is shown on Fig. 3. The spatial arrangement of all tethers is defined by $\mathbf{s}_i$: