Renewable Energy 93 (2016) 27–37

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

An optimal arrangement of mooring lines for the three-tether submerged point-absorbing wave energy converter

N.Y. Sergiienko*, B.S. Cazzolato, B. Ding, M. Arjomandi

The University of Adelaide, School of Mechanical Engineering, Adelaide, Australia

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form
10 February 2016
Accepted 17 February 2016
Available online 27 February 2016

Keywords:
Wave energy
Wave energy converter
Submerged point absorber
Three-tether mooring

ABSTRACT

Point-absorbing wave energy converters (WECs) with a single-tether mooring are capable of extracting power from heave motion, but they do not utilise the full energy harvesting potential. One of the possible ways to increase the total power absorption is to add another controllable degree of freedom. These can be achieved by using a so-called 'tripod' configuration when the body is tied to three tethers attached to the power take-off systems at the sea floor. This paper investigates the optimal inclination of tethers considering two different approaches: a purely kinematic analysis, not taking into account the shape of the buoy and a dynamic analysis of spherical and cylindrical WECs, using a linear frequency-domain method. The results show that for a submerged sphere and for a submerged vertical cylinder with an aspect ratio of one, tethers should be orthogonal to each other, forming edges of the cuboidal vertex. Such a configuration of tethers provides for uniform performance of the WEC in all directions of motion. However, for the cylinders with an aspect ratio other than one, an optimal angle between the tethers depends greatly on the ratio between the cylinder height and diameter.

1. Introduction

Ocean waves are a huge resource of renewable energy with great potential to be captured and employed for electricity generation and water desalination. Many concepts for extracting energy from surface waves have been realised, leading to more than 200 different wave energy converters (WECs) in various stages of development [1]. Despite the wide variety of WECs technologies on offer, floating and fully submerged point absorbers comprise a great proportion of existing full-scale prototypes of WECs, which typically operate in deep water waves with high energy content [2]. In most cases, a point absorber, whose dimensions are smaller than a wavelength, is designed as an axisymmetric buoy with the main advantage being insensitive to wave direction [3].

An axisymmetric body as a prospective WEC has been thoroughly studied in Refs. [4–6], showing that its maximum power absorption is independent of the scale of the device and is a function of the wavelength of an incident wave and oscillatory modes of the body. The majority of existing point-absorbing WECs operate only in the heave mode, limiting energy extraction to approximately one third of the available energy [7]. Such considerable attention to the heaving buoys can be explained by the relative simplicity of the design and the lower capital cost as compared with WECs with multiple degrees of freedom. However, a point absorber that oscillates in two modes (heave/surge or heave/pitch) with optimal control parameters can theoretically capture three times more power than a heaving device, achieving the maximum power absorption for such types of WECs [7].

Depending on the power take-off (PTO) operating principle and type of mooring configuration, existing WECs with multiple degrees of freedom can be divided into two categories (similar to the classification in Ref. [8]):

(i) WECs that utilise slack mooring lines just to keep a body on site (Fig. 1a). Such mooring configurations are not involved in power generation and have been applied to the floating WECs, such as SEAREV [9] or Pelamis [3]. The power take-off system of these devices is located inside the buoy's hull, that can impose constraints on the size of the system.

(ii) Floating or fully submerged energy converters where the mooring legs are always under tension (Fig. 1b). In this configuration, tethers can be attached through spools to the electrical generators, as is implemented in the 3D-WEC that is under development by Resolute Marine Energy, Inc. [10],

---

* Corresponding author.
E-mail address: nataliia.sergiienko@adelaide.edu.au (N.Y. Sergiienko).

http://dx.doi.org/10.1016/j.renene.2016.02.048
0960-1481/

Nomenclature

A	amplitude of the incident wave
$\mathbf{A}, \mathbf{B}$	hydrodynamic added mass and damping coefficient matrix
$\mathbf{F}_{exc}$	incident wave excitation force
$\mathbf{F}_{pto}$	force exerted on the WEC due to the power take-off system
$\mathbf{F}_{rad}$	hydrodynamic radiation force
G	buoy centre of mass
H	WEC (cylinder) height
$\mathbf{I}_3$	identity matrix of size 3 × 3
$\mathbf{J}^{-1}, \bar{\mathbf{J}}^{-1}$	inverse kinematic Jacobian of the WEC: conventional and dimensionally homogeneous
N_i, L_i	attachment points of the i-th tether to the buoy hull and sea floor respectively
$\mathbf{N}_0, \mathbf{S}_0$	skew-symmetric matrices that represent $[\mathbf{n}_0]_\times^\top$ and $[\mathbf{s}_0]_\times^\top$ respectively
P	WEC power absorbed
T	dynamic tension in the tether
$\mathbf{Z}_{buoy}, \mathbf{Z}_{pto}$	hydrodynamics impedance of the buoy and impedance of the PTO system
a	WEC radius
$c_t, \mathbf{C}_t, \tilde{\mathbf{C}}_t$	power take-off damping: coefficient, matrix for one tether and a collective matrix for all tethers
$\mathbf{e}_{si}$	unit-vector directed along i-th tether
$\mathbf{f}_t$, τ_t,	force and torque applied from the tether to the buoy
d_s	submergence depth of the WEC (distance from the sea water level to the WEC centre of mass)
g	gravitational acceleration
h	water depth
k	wavenumber ($\omega^2 = gk \tanh kh$)
$k_t, \mathbf{K}_t, \tilde{\mathbf{K}}_t$	power take-off stiffness: coefficient, matrix for one tether and a collective matrix for all tethers
l_i	dynamic length of the i-th mooring line
$m_b, \mathbf{M}$	WEC mass and mass matrix
m_w	mass of water displaced by the WEC
$\mathbf{n}_i$	position vector of the i-th tether attachment point relative to the buoy centre of mass
$\mathbf{q}$	vector of three leg length variables
$\mathbf{r}$	vector of linear displacements of the WEC
$\mathbf{s}_i$	vector directed along i-th tether
$\mathbf{x}$	6 DoF WEC position vector
α	inclination angle of each tether to the vertical
$\delta(\bullet)$	change in vector or scalar from nominal position
γ_0	distribution of the tether tension force over its length
κ	condition number
ω	radial wave frequency
ρ	water density
θ	angle between two tethers in the plane that they form
ϑ	vector of angular displacements of the WEC

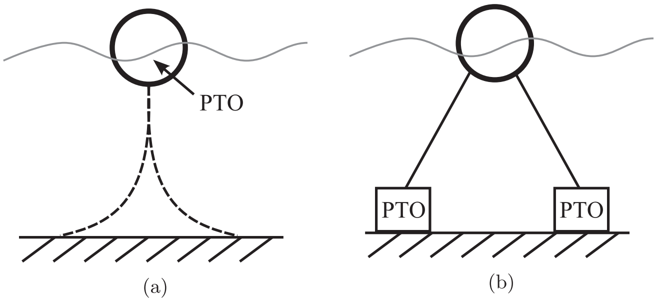

Fig. 1. A schematic representation of mooring configurations: (a) slack mooring lines, (b) tension leg moorings.

or to a piston of a hydraulic PTO system. A solo-duck WEC, developed by The University of Edinburgh [11], can also be classified in this category.

Although the effect of slack mooring lines on the performance of the floating WECs has been assessed in Refs. [12–14], a mooring configuration with tethers under tension is of more practical interest for submerged buoys due to the required positive buoyancy of the WEC.

An axisymmetric body needs to oscillate in two modes (radiating symmetric and antisymmetric waves) to absorb the maximum available energy [7]. Even though a body is symmetrical about a vertical axis, the addition of mooring lines makes the whole system asymmetric and therefore sensitive to the direction of wave propagation. This means that a WEC should oscillate along the vertical axis (heave) radiating symmetric waves, and in a horizontal plane (surge-sway or pitch-roll) radiating antisymmetric waves along the axis aligned with the propagation of incident waves. Having three motion modes that need to be controlled, intuitively, the minimum number of tethers in a mooring configuration is also three. Moreover, hydrodynamic forces that act on the axisymmetric body are uncoupled for surge, sway and heave, but are coupled for surge/pitch and sway/roll motions [7]. Therefore, ideally, the mooring design should not impose additional coupling between modes.

A system with a three-cable mooring of a submerged sphere was first proposed in Ref. [15]. The configuration, where three cables are equally inclined to the vertical and situated symmetrically around a sphere, provides an independence of surge, sway and heave motions, while all three modes are dependent on the parameters of a power take-off system and an inclination angle of cables [15]. Wave-to-wave tuning of the PTO parameters is an objective of a WEC control system, whereas the inclination angle of the cables cannot be changed during the life-span of the device and should be optimised during the design stage to maximise energy harvesting. However, the system in Ref. [15] was explored with only two inclination angles of the cables: 45 and 60°, and the dependence of the power absorption on the angle has not yet been explored. A similar tripod WEC design has been used as a benchmark device in Refs. [10,16] to test a developed optimal causal control system. This WEC consists of a floating cylinder attached to three tethers that are inclined to the vertical by 63.5°, which seems to have been chosen arbitrarily by the researchers. To the best knowledge of the authors, these studies are the only ones that have considered a WEC with multiple degrees of freedom using a three-leg mooring. Consequently, the question of an optimal mooring configuration that maximises absorbed power remains open and is discussed in this paper.

In this research, the tripod system is investigated for a fully submerged point-absorbing WEC, similar to the CETO system developed by Carnegie Wave Energy Limited [17]. Section 2 studies the problem from the kinematics point of view without taking into