Applied Ocean Research 63 (2017) 90–105

Contents lists available at ScienceDirect

Applied Ocean Research

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

Numerical modelling of a point-absorbing wave energy converter in irregular and extreme waves

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ARTICLE INFO

Article history:
Received 19 July 2016
Received in revised form
28 December 2016
Accepted 4 January 2017

Keywords:
Point-absorbing WEC
CFD
Irregular waves
Extreme waves
Connection rope tension
Survivability

ABSTRACT

Based on the Navier-Stokes (RANS) equations, a three-dimensional (3-D) mathematical model for the hydrodynamics and structural dynamics of a floating point-absorbing wave energy converter (WEC) with a stroke control system in irregular and extreme waves is presented. The model is validated by a comparison of the numerical results with the wave tank experiment results of other researchers. The validated model is then utilized to examine the effect of wave height on structure displacements and connection rope tension. In the examined cases, the differences in WEC's performance exhibited by an inviscid fluid and a viscous fluid can be neglected. Our results also reveal that the differences in behavior predicted by boundary element method (BEM) and the RANS-based method can be significant and vary considerably, depending on wave height.

1. Introduction

Wave energy as a renewable source with high power-density has drawn increasing attention in many countries since 1990s [1]. Point-absorbing wave energy converters (WECs) possess the advantages of small size, low cost and simple construction. Several point-absorbing WECs have been developed at Uppsala University, Sweden, and installed at the test site offshore Lysekil on the Swedish west coast [2] within the Lysekil project, see Fig. 1. Each WEC consists of a point-absorbing buoy floating on the water surface linked through a connection rope to a direct driven linear generator placed on the seabed, see Fig. 2. The buoy moves with waves, dragging the translator inside the generator to move up and down, inducing a voltage in the stator windings. Stroke length of the translator is limited by end stops (see Fig. 2) [3,4]. The WEC dimensions are adjusted to the Lysekil wave climate with the significant wave height of 1.5–2.0 m and energy period of 5.0–6.0 s [5]. Similar wave energy conversion concepts (a point-absorbing WEC with a linear generator power take-off) are used in a number of other projects [6,7], where the direct driven solution enables a robust design [8].

One of the main problems in wave energy utilization is the survivability of WECs in extreme waves [9]. Facing extreme waves even for a short period of time may lead to fatal consequences for the WEC [10]. In the present paper, 'extreme', also called freak or rough, waves mean abnormally large amplitude waves, whose heights exceed 2.2 times the significant wave height of the background sea [11]. These extreme waves are rare, however, possess deadly threats to WECs. Taking WECs in the Lysekil project for instance, it was found that the connection rope tension would be extremely large in extreme waves [12]. The connection rope is a vital part of the WEC power take off (PTO) system. If the connection rope failed, the translator would not move any more, resulting in the failure of the whole system and zero energy production. In order to ensure survivability of WECs under an extreme wave condition, avoiding high maintenance cost, it is essential to investigate performance of the WEC in extreme waves. Although the interaction of waves and point-absorbing WECs has been extensively studied analytically and numerically, most of these studies are limited to small waves-structure interaction [13–16].

The potential flow theory is often used to describe linear wave-structure interaction. Eriksson et al. [4] presented a model for a heaving point absorber with a linear PTO and limited stroke length based on the linear potential wave theory and evaluated its performance on capturing power under normal wave conditions. A simple point-absorbing WEC was studied by Sheng et al. [17],

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http://dx.doi.org/10.1016/j.apor.2017.01.004
0141-1187/

Nomenclature

A_{fac}	Active area of the stator
A_n	Real part of the Fourier transform of $\eta(t)$
B_n	Imaginary part of the Fourier transform of $\eta(t)$
D	Water depth
D_b	Buoy diameter
$\hat{e}_{rb}$	Unit vector in radial direction from pole to the buoy
$\hat{e}_{rt}$	Unit vector in radial direction from pole to the translator
f	Friction damping value
$\mathbf{F}_0$	Downward force on the translator in initial position
$\mathbf{F}_{\text{cen}}$	Centrifugal force acting on the buoy
$\mathbf{F}_{\text{cor}}$	Coriolis force acting on the buoy
$\mathbf{F}_d$	Damping force acting on the translator
$\mathbf{F}_e$	End spring force
$\mathbf{F}_h$	Hydrodynamic force acting on the buoy
$\mathbf{F}_s$	Retracting spring force acting on the translator
$\mathbf{F}_t$	Force in the connection rope
$\mathbf{g}$	Gravitational acceleration
H_b	Buoy height
H_n	Wave height of the n-th linear wave composing the irregular wave
H_s	Significant wave height
$\mathbf{I}$	Unit tensor
k_l	Stiffness of the lower end stop spring
k_s	Stiffness of the retracting spring
k_u	Stiffness of the upper end stop spring
l_l	Lower free stroke length
l_{mu}	Upper maximum stroke length
l_{ml}	Lower maximum stroke length
l_s	Length of the stator
l_t	Length of the translator
l_u	Upper free stroke length
m_b	Mass of the buoy
m_t	Mass of the translator
M_b	Moment of inertia of the buoy
N	Total sampling number of the interested wave series
$\mathbf{n}$	Unit normal vector of the buoy's surface element
$\mathbf{n}_A$	Unit vector normal to the surface of local control volume
$\mathbf{N}_h$	Moment of the hydrodynamic force acting on the buoy with respect to buoy center
p	Fluid pressure
$\mathbf{r}_b$	Position vector of the buoy
$\mathbf{r}_s$	Position vector of the point on a local buoy surface
$\mathbf{r}_t$	Position vector of the translator
$\mathbf{S}$	Body force
S_d	Momentum damping term in z-direction
$\mathbf{T}$	Stress tensor
T_e	Wave energy period
T_{tot}	Total time of the interested wave series
$u_x(t)$	Horizontal water particle velocity at inlet boundary
$u_z(t)$	Vertical water particle velocity at inlet boundary
$\mathbf{v}$	Fluid velocity vector
$\mathbf{v}_A$	Velocity of the *CV* surface
$\mathbf{v}_b$	Velocity of the buoy
$\dot{\mathbf{v}}_b$	Accelerations of the buoy
$\mathbf{v}_{\theta b}$	Tangential velocity of the buoy
$\mathbf{v}_{rb}$	Radial velocity of the buoy
$\mathbf{v}_s$	Velocity vector of the buoy on the fluid-structure interface
$\mathbf{v}_t$	Velocity of the translator
$\dot{\mathbf{v}}_t$	Accelerations of the translator
x_e	End position of the added dissipation zone in the x-direction
x_s	Start position of the added dissipation zone in the x-direction
z_b	Bottom position of the dissipation zone in the z-direction
z_{fs}	Free-surface position of the dissipation zone in the z-direction
z'	Vertical distance from the base of the model to the water particle at inlet boundary
α	Volume fraction
β_b	Magnitude of the pitch angular displacement of the buoy
γ	Damping coefficient
$\Delta\mathbf{r}_b$	Displacement of the buoy from the initial position
Δr_b	$\Delta r_b = \Delta\mathbf{r}_b \cdot \hat{e}_{rb}$
$\Delta\mathbf{r}_t$	Displacement of the translator from the initial position
Δr_t	$\Delta r_t = \Delta\mathbf{r}_t \cdot \hat{e}_{rt}$
ε_n	Wave phase angle of the n-th linear wave composing the irregular wave
$\eta(t)$	Wave elevation
$I(\omega_n)$	Fourier transform of $\eta(t)$
μ	Dynamic viscosity of the fluid
μ_g	Gas dynamic viscosity
μ_l	Liquid dynamic viscosity
μ_t	Turbulent viscosity of the fluid
ρ	Fluid density
ρ_g	Liquid density
ρ_l	Gas density
$\boldsymbol{\omega}_b$	Pitch angular velocity of the buoy
$\dot{\boldsymbol{\omega}}_b$	Angular acceleration of the buoy
ω_n	Angular frequency of the n-th linear wave composing the irregular wave

based on the boundary element method (BEM). It was found that an active PTO force control – optimizing the average power output frequency-dependent damping, fully optimized (the optimum phase and average power output control) damping and latching – can considerably improve wave energy conversion efficiency when compared to the constant damping. Harnois et al. [18] verified a numerical model for mooring systems of a floating point absorber in both regular and irregular waves, based on the linear potential wave theory, however, without considering extreme waves. Recently, performance of a point-absorbing WEC within the Lysekil project was studied by Hai et al. [19] numerically in equivalent electric circuits based on the linear potential wave theory. Compared against sea trial results, it was found that the method estimated the average captured power properly, however, overestimated the connection rope force significantly (with a difference of up to 40% of the predicted force) under energetic sea states. Many efforts have been devoted to improving wave energy conversion efficiency [14,15,20–22]. The majority of this work so far has been concentrated on linear waves, and well elucidated fundamental mechanism of underlying linear wave-structure interaction for a point absorber with and without considering a passive and active PTO force control. Nevertheless, complex free surface phenomena such as flow separation, wave breaking and overtopping, which are common phenomena when large enough waves hit floating bodies, have not been considered despite being important for evaluating the performance of a point absorber in severe wave conditions.