Ocean Engineering 129 (2017) 374–381

Contents lists available at ScienceDirect

Ocean Engineering

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

Dynamic behavior of a wave power buoy with interior on-board linear generator

Bing Chen[a,*], Tom Bruce[b], Clive A. Greated[c], Haigui Kang[a]

[a] School of Ocean Science and Technology, Dalian University of Technology, Panjin, China
[b] Institution for Energy system, The University of Edinburgh, Scotland, UK
[c] School of Physics and Astronomy, The University of Edinburgh, Scotland, UK

ARTICLE INFO

Keyword:
Wave buoy
Hydrodynamic performance
Linear generator
Primary conversion efficiency

ABSTRACT

Wave energy conversion is attractive from the viewpoint of the size of the renewable resource, but prototypes continue to suffer from high costs, leading to the idea of combining a wave energy conversion function with a conventional function of another ocean or coastal infrastructure to achieve cost-sharing between functions. Here, a wave power device in which a linear generator is installed inside a sealed floating horizontal circular cylindrical buoy is studied, which has dual functions of a wave power converter and a floating breakwater. A two-dimensional Navier Stokes numerical wave tank is used, together with a Volume of Fluid method to model the detail of the buoy-wave interaction. After model validation, the primary conversion efficiency of the device, and the wave transmission and reflection coefficients are explored. It is found that the maximum primary conversion efficiency is close to 25%. In resonant state, the amplitude of the translator's relative oscillation could be much larger than that of incident wave. When the incident wave frequency departs from the natural frequency of the linear generator, the energy conversion efficiency deteriorates rapidly. When wave energy conversion reaches maximum efficiency, the corresponding wave transmission coefficients are in the range of 0.7–0.75, and the corresponding wave reflection coefficients are in the range of 0.2–0.3.

1. Introduction

As one of the primary marine renewable energy resources, wave energy has a promising future for energy harvesting. As well as potentially being a major input source for the grid it also has advantages where a high power self-contained supply is required notably for ocean resource exploration. So far the relatively successful wave energy technologies currently in operation or in the testing stage include oscillating water column devices (*e.g.* Limpet), flapping board devices (*e.g.* Oyster), floating hull devices (*e.g.* Pelamis) and point-absorbing wave buoys (*e.g.* Welo, Power Buoy, Ceto and Seatricity). These are built either on the shore line, mounted on underwater foundations in shallow waters, or moored in intermediate or deep water. All of them suffer from the high cost of infrastructure and maintenance due to the strict requirements of survivability in severe wave climates. Another challenge faced is corrosion from sea water leading to damage of bearings, hydraulic cylinders and other equipment, seriously lowering the reliability of the converter. For a technically and financially feasible solution to wave energy utilization, ease of deployment, survivability and reliability must be comprehensively taken into account with power conversion efficiency not necessary being the first priority.

An option for addressing the high cost of infrastructure is to incorporate the wave energy device as part of another ocean engineering structure that already has its own mooring or foundation system. One attractive possibility is to combine a wave energy device with a floating breakwater and in order to assess the viability of this. Chen and Ning et al. (2016) have used numerical simulation to assess the performance of floating circular cylinders perpendicular to the direction of wave propagation serving as both floating breakwaters and wave energy converters.

The power takeoff system in current wave energy devices is generally an air turbine (*e.g.* Limpet; Owel), a hydraulic system coupled to a generator (*e.g.* Pelamis) or an onshore water turbine (*e.g.* Oyster, Seatricity and Ceto). In our study we examine the use of a linear generator as power takeoff system which has many advantages such as structural simplicity and high efficiency. Direct drive power conversion systems of this type can be completely isolated from sea water thus avoiding the serious problems associated with corrosion, reducing the cost of maintenance and making the system more reliable.

A number of direct drive wave energy converters have been proposed. Some of these (*e.g.* Wello) rely on a rotating part inside a

* Corresponding author.
E-mail addresses: chenbing@dlut.edu.cn (B. Chen), Tom.Bruce@ed.ac.uk (T. Bruce), c.a.greated@ed.ac.uk (C.A. Greated).

http://dx.doi.org/10.1016/j.oceaneng.2016.11.050
Received 23 June 2016; Received in revised form 7 November 2016; Accepted 26 November 2016
0029-8018/

buoy-type device being coupled directly to the electrical generator (Mueller and Baker, 2005) whilst others (*e.g.* Wavestar) link floating elements to a rigid structure by means of rotating arms (Hansen et al., 2011). Linear generators have also been implemented successfully, notably in the Lysekil Project (Leijon et al., 2009) in which a three phase permanent magnet linear generator is fixed to the sea bed and attached to a point-absorbing buoy on the surface by a line and also in the Archimedes Waveswing System (Polinder et al., 2004). There have been a number of studies examining the electromagnetic design of linear generators used for wave energy extraction, mostly simplifying the waves as being monochromatic (Kimoulakis and Kladas et al., 2009; Prudell and Stoddard et al., 2010; Ivanova and Ågren et al., 2005; Wolfbrandt, 2006).

In this study we examine a wave power device in which a linear generator is installed inside a sealed floating horizontal circular cylindrical buoy. This can act as a wave power converter and also simultaneously serve as a floating breakwater. Previously Chen and Ning et al. (2016) had developed a numerical wave tank based on an incompressible viscous flow model and the equations of motion of a floating cylinder. In that previous study the wave force pushes the cylinder against a resistive force representing the load of the electrical generator. In this study the same flow model is used and the floating cylinder serves again as a wave power buoy but with an interior on-board linear generator, the translator of the linear generator moving relative to the cylinder. The load in the electrical circuit and the resistive loss are modelled by a damping force which restrains the motion of the translator. The dynamic response of this buoy-translator system to wave action is studied by numerical simulation. The motions of the cylinder and the translator of the on-board liner generator, the wave transmission and reflection coefficients and the primary conversion efficiency of wave power are all analyzed.

2. Numerical model

2.1. Flow model

A two-dimensional numerical wave tank based on the Navier-Stokes equations for an incompressible viscous fluid is established and the governing equations are spatially discretized by the finite element method. The Arbitrary Lagrangian-Eulerian (ALE) method is applied to analyze the wave-cylinder interaction. Smagorinsky (1963) subgrid scale model (SGS) is employed as turbulence closure. The ALE representations of the spatially filtered continuity equation and Navier-Stokes equations are written as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + (u_j - u_{meshj})\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \upsilon\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}\right) + \frac{\partial \tau_{ij}}{\partial x_j} + f_i \tag{2}$$

in which the SGS stress τ_{ij} is represented by an eddy viscosity model:

$$\tau_{ij} = \upsilon_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{1}{3}\delta_{ij}\tau_{kk} \tag{3}$$

where the eddy viscosity is expressed as:

$$\upsilon_T = (C_s\Delta)^2\sqrt{2S_{ij}S_{ij}}, \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{4}$$

In the above equations the subscripts i, j=1, 2 represent the directions of Cartesian coordinates; δ_{ij} is Kronecker delta, S_{ij} the strain rate tensor; u and u_{mesh} are the velocities of the fluid particles and mesh, respectively; p is the pressure, ρ the fluid density and υ the kinematic viscosity of the fluid. C_s is constant for the Smagorinsky SGS model, taken as 0.1. The filter scale of the SGS model Δ is proportional to the grid size; for a two dimensional problem it is the square root of the area of a grid cell; f is the volumetric force *i.e.* gravity in this paper.

A CLEAR-VOF model proposed by Ashgriz and Barbat et al. (2004) is adopted in this study to trace the water surface. The idea of this model is to move the fluid portion of an element in a Lagrangian sense, and redistribute it locally in the Eulerian fixed mesh. The Navier-Stokes equation is marching in time with a three-step algorithm, comprised of evaluating the velocities with momentum equations explicitly and solving a Poisson equation for pressure implicitly, *cf.* Jiang and Kawahara et al. (1992).

Biésel (1951) obtained the first order analytical solution for relatively long waves generated by a sinusoidally moving piston-type wave maker and Madsen (1971) extend the theory to second order accuracy. Furthermore, by giving the wave maker a motion that consists of both first and second harmonics, a parasitic second harmonic free wave may be eliminated to obtain a permanent wave profile along the tank. Madsen's (1971)' theory has been adapted to establish numerical wave tanks, such as the work of Dong and Huang (2004). In this paper, Stokes second-order waves are generated following Madsen (1971)'s theory. The displacement ξ of the piston of the wave generator is given as:

$$\xi(t) = -\xi_0\left[\cos\omega t + \frac{a}{2h_0n_1}\left(\frac{3}{4\sinh^2 kh_0} - \frac{n_1}{2}\right)\sin 2\omega t\right] \tag{5}$$

$$\xi_0 = \frac{an_1}{\tanh kh_0},\ n_1 = \frac{1}{2}\left(1 + \frac{2kh_0}{\sinh 2kh_0}\right) \tag{6}$$

where h_O is the still water depth at the wave generation boundary; ω is the angular frequency of the wave, k the wave number and a the wave amplitude. Thus the horizontal component of the wave generator's velocity can be derived from Eq. (5) as:

$$U(t) = \frac{\partial\xi}{\partial t} = \xi_0\omega\left[\sin\omega t + \frac{a}{h_0n_1}\left(\frac{3}{4\sinh^2 kh_0} - \frac{n_1}{2}\right)\cos 2\omega t\right] \tag{7}$$

When a wave passes the cylinder and finally hits the end wall of the tank, it must be absorbed so that no reflected waves are transmitted back to the cylinder. This can be done by placing a piston type wave absorber at the end of the tank, the piston of the wave absorber moving as:

$$U_{ab}(t) = -\Delta\xi\cdot\omega\left[\sin\omega t + \frac{a}{h_0n_1}\left(\frac{3}{4\sinh^2 kh_0} - \frac{n_1}{2}\right)\cos 2\omega t\right],\ \Delta$$
$$\xi = \xi_0\left[\frac{\eta(t) - SWL}{a}\right] \tag{8}$$

In a similar way, a slight reflection backwards from the cylinder can be absorbed by a correction on the wave generator's motion by measuring how much the water elevation differs from the predicted value. This actually turns the wave generator at the left end of the tank into a wave generator-absorber.

A non-slip velocity condition was applied on the surface of the cylinders. On other boundaries including wave generator, wave absorber and seabed, full slip conditions of velocity were applied:

$$(u_1, u_2) = (0, \dot{z}_c) \quad , \quad on\ \ surface\ \ of\ \ cylinder u_1 = U_w,$$
$$on\ \ wave\ \ generator u_1 = U_{ab}, \quad on\ \ wave\ \ absorber u_2 = 0 \quad ,$$
$$on\ \ seabed \tag{9}$$

$\dot{z}_c$ is the velocity of the floating cylinder, found from the equation of motion of the cylinder.

Above the free surface of the water, the pressure was set to be atmospheric *i.e.* p=0. At the beginning of the simulation, velocities were set to zero, and the pressure was set to the static still water pressure.