

Control of a Point Absorber Wave Energy Converter

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Abstract- This paper deals with the optimization of a bottom fixed heaving point absorber wave energy converter (PAWEC) type. The PAWEC consists of a unique horizontal cylinder of radius R and length L , connected to the seabed through an extensible Power Take Off device. In this work, an original control strategy is used in order to optimize the PAWEC. The proposed method links the damping coefficient of the Power Take Off device to the relative velocity between the buoy and the wave. This study focus on the comparison of the two cases where a passive control is adopted and where the damping coefficient is a constant. The performance of the wave energy converter (WEC) in different wave conditions for each of the two cases is investigated. The results show that the recovered energy is considerably increased owing to the adaptation of the damping coefficient with the buoy speed.

Keywords Wave energy converters, heaving point absorber, passive control, evolutionary algorithm, WEC performance, Morison's force

1. Introduction

In the past decades, many wave energy converters (WECs) have been developed, among them are Pelamis [1], Searev [2] and Wavestars [3]. Polinder and Scuotto [4] introduced the wave energy converters and their impact on power systems. Drew et al. [5] presented several wave energy converter (WEC) device types and discussed some Power Take Off systems and control strategies that are used to enhance their efficiency. Falcão [6] established the development of wave energy utilization since 1970 and shows the recent situation of different wave energy systems. He pointed up that the development of wave energy converters is a slow and expensive process. Jabrali et al. [7] studied an articulated freely floating WEC which consists of two cylinders connected with a flat plate. The results show the effects of various parameters on the recovered energy by using an evolutionary algorithm method. Further reviews of these technologies can be found in [8-13]. Among the various existing types of wave energy converters, the Point Absorbers (PA) are of particular interest in view of their widespread use and the relative ease of their modeling. The Point Absorber is defined [14-15] as a floating body oscillating with one or more degrees of freedom with dimensions that are small compared to the incident wavelength. In order to recover as much energy as possible from the use of a Point Absorber, the effects of many parameters, including the state of the waves, the dimensions and geometry of the buoy, the characteristics of the Power Take Off system (PTO), must be taken into account.

The main goal is to make their interactions converge towards an optimal use for the benefit of the energy recovery process. Jabrali et al. [16] investigated the effect of drag coefficient on efficiency of a Point Absorber (PA). The recovered energy is calculated for different drag coefficients. The Morison equation is used to add drag and added mass effects. The results show that the recovered energy is a decreasing function of the drag coefficient.

More particularly, focusing on the PTO subsystems and on the determination of optimal parameter's values for their function, several approaches for their optimization and control are used. It should be noted that there are different types of PTO devices [17], which can be broadly divided into five main categories: air turbines, hydraulic converter, hydro turbines and direct mechanical or electrical drive system [18], with each category conferring specific advantages. However, from the point of view of floating WEC modeling, the PTOs will essentially act through the damping and restoration forces that they generate. In the present paper, the used PTO consists of a linear damper who is considered as direct driven linear generator.

Falnes [19] presented a review of control methods used to increase the power output of wave energy converters. Hals et al. [20] applied a selection of strategies for real-time control of wave energy converters to the example of a heaving-buoy wave absorber. The strategies include approximate complex conjugate control; controlled tracking of the approximate optimum velocity, latching and clutching algorithms as well

as a model-predictive controller. Zou and Abdelkhalik [21] investigated numerical tests and comparisons of a few recently developed control methods. Rather [21] conclude that a theoretically optimal controller might not be optimal when tested in a practical test environment. In particular, considerations that needed to be accounted for in designing a control method for WEC systems has been presented. These considerations concern the limitation of the maximum achievable PTO control force and limitation due to the maximum attainable displacement of the WEC system. Another consideration is the ability of the PTO to track the control command. Other works on the control strategy can be found in [22-27].

Generally, the PTO's force is decomposed into two parts; one is related to the velocity of the buoy $\dot{y}(t)$ and the other to the displacement $y(t)$, this PTO force is expressed as $F_{pto}(t) = -\beta\dot{y}(t) - Ky(t)$, where β and K are coefficients that should be positive. Two main strategies developed for the electrical control are passive [28] and active control [29]. For passive control, the reactive component K is set to zero, and only β is controlled. The active control necessitates tuning of both β and K , which requires bidirectional power flow between the PTO and the device. The advantages of the passive control are the simple implementation and increase of the mean power produced by the WEC [30].

In this paper, an original passive control strategy is used in order to optimize a heaving point absorber WEC (PAWEC). The proposed method defines a relationship between the damping parameter and the powers of the relative speed between the buoy and the fluid. The law considered is of the "power law" type in the form of polynomial function. The values of the polynomial coefficients are obtained by using an evolutionary algorithm optimization method. The considered point absorber consists of a unique cylinder of radius (R) and length (L), oscillating under the action of sea waves and connected to the seabed through an extensible Power Take Off device. The pressure and the viscous forces acting on the wetted surfaces of the cylinder are modeled by the Morison equation which is the force that modelling the inertia and drag forces exerted by the fluid on the cylinder (Eq.2).

This paper is organized as follows: the first section is devoted to the mathematical models of the considered systems and examines the identification of the drag and added mass coefficients; the second section deals with the PTO optimization and the investigation of the PAWEC performance.

2. Mathematical modeling

The bottom fixed heaving point absorber wave energy converter (PAWEC) consists of a cylindrical buoy of a radius (R) connected to the seabed by an extensible Power Take off device. Let $\mathcal{R}(O, \vec{x}, \vec{y}, \vec{z})$ to be non-inertial reference frame, where O is an arbitrary point of the moving free surface of the fluid, \vec{y} is the upward vertical and the Cartesian coordinates x , y indicates the position of the center O_1 (Fig. 1). Only heave motions of the buoy are allowed and are related to the variable y .

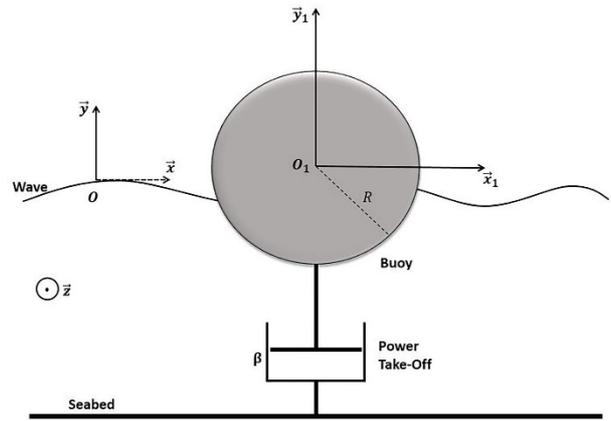


Fig. 1. Schematic illustration of PAWEC where $\mathcal{R}(O, \vec{x}, \vec{y}, \vec{z})$ is the reference frame linked on a point O placed randomly at the free surface of the fluid and $\mathcal{R}_1(O_1, \vec{x}_1, \vec{y}_1, \vec{z}_1)$ is the reference frame associated to the cylinder.

In the non-inertial frame $\mathcal{R}(O, \vec{x}, \vec{y}, \vec{z})$, the time domain equation according to Newton's second law of motion is

$$m \ddot{y} \vec{y} = \vec{P} + \vec{F}_a + \vec{F}_{pto} + \vec{F}_m - m \frac{d^2 \eta(t)}{dt^2} \vec{y} \quad (1)$$

where m is the cylinder mass, $\vec{P} = m\vec{g}$ is the gravity force and $\vec{g} = -g\vec{y}$ is the gravity acceleration, \vec{F}_a is the Archimedes thrust, \vec{F}_{pto} is the force exerted by PTO system on the buoy and \vec{F}_m is the Morison force modelling the inertia and drag forces exerted by the fluid on the cylinder. The term $m \frac{d^2 \eta(t)}{dt^2}$ is the inertia force due to the non-inertial reference frame, where $\eta(t) = A_m \cos(\omega t)$ represent the vertical distance between a point on the free surface of the fluid and the average level of the fluid at rest, A_m is the amplitude of the wave, $\omega = \frac{2\pi}{T}$ is the pulsation of the wave and T is the wave period.

Morison's force \vec{F}_m proposed by Morison et al. [31] is written as:

$$\vec{F}_m = \rho_e C_m V \ddot{y} \vec{y} + \frac{1}{2} \rho_e C_d S \dot{y} |\dot{y}| \vec{y} \quad (2)$$

where \dot{y} and \ddot{y} are respectively the velocity and the acceleration of the cylinder, ρ_e is the fluid density, C_m and C_d are the inertia and the drag coefficients, $S = RL \text{Arccos}(\frac{y}{R})$ is the wetted cross-section area of the cylinder, L is the length of the cylinder, R is the radius and V is the volume of the body.

The Archimedes force is $\vec{F}_a = -\rho_e V_i \vec{g}$, where V_i is the immersed volume.

The PTO force defined as $\vec{F}_{pto} = -\beta V_B \dot{y} \vec{y}$ where β is a coefficient related to the Power Take Off device and $V_B = y - A_m \omega \sin(\omega t)$ is the velocity of the buoy. In order to improve the recovered energy by the PTO device, we introduce the damping coefficient as a polynomial function related to the velocity of the cylinder and written as

$$\beta = \sum_{i=0}^N a_i V_B^i = \sum_{i=0}^N a_i (y - A_m \omega \sin(\omega t))^i \quad (3)$$

where $a_i, i = 0..N$ are coefficients to be determined. For this end, we propose to assign the values of the coefficients a_i in order to satisfy optimization conditions of maximum

recovered energy by the WEC. A genetic algorithm is used to determine these optimal values.

The insertion of the expressions of the forces in Eq. (1) leads to the following differential equation

$$(m + \rho_e C_m V_i) \ddot{y} + \beta (\dot{y} - A_m \omega \sin(\omega t)) + mg + \frac{1}{2} \rho_e C_d S \dot{y} |\dot{y}| - \rho_e g L R^2 \left[\theta_L + \frac{\eta_1 + \eta_2}{2R} + \frac{1}{4} \left(\sin \left(2 \left(\theta_L + \frac{\eta_1}{R} \right) \right) + \sin \left(2 \left(\theta_L + \frac{\eta_2}{R} \right) \right) \right) \right] + \rho_e g L R y \left(\sin \left(\theta_L + \frac{\eta_1}{R} \right) + \sin \left(\theta_L + \frac{\eta_2}{R} \right) \right) - m A_m \omega^2 \cos(\omega t) = 0 \quad (4)$$

where $\theta_L = \arccos \left(\frac{y}{R} \right)$, $\eta_1 = A_m \cos(\omega t + kR \sin \theta_L)$ and $\eta_2 = A_m \cos(\omega t - kR \sin \theta_L)$, k is the wave number. The Eq. (4) with initial conditions $y(t=0)$ and $\dot{y}(t=0)$ can be solved numerically by using the 4th order Runge-Kutta method as long as that the values of C_m , C_d and a_i are known.

When using the Morison approach to model fluid actions on the buoy, as is the case here, the appropriate values of drag and inertia coefficients must be determined. In order to find the optimum values of C_m and C_d , a comparison is made between a numerical solution calculated using a Boundary Element Method (BEM) code and the solution obtained by the mathematical model based on the Morison equation. Optimal values of the coefficients C_m and C_d are fixed by minimizing the gap between the two solutions. For this, an evolutionary algorithm [32] is used. It should be noted that the objective function E_r , adopted for the minimization process is the sum of the squares of the gaps between the two solutions and is written as $E_r = \sum_{t=t_1}^{t_2} (y_{BEM}(t) - y(t))^2$ where $y_{BEM}(t)$ and $y(t)$ are respectively the position of the WEC obtained by the BEM code and by the Morison approach.

For the implementation of the evolutionary algorithm, iterations are initialized by creating a first generation of solutions with random values of the coefficients C_m and C_d , for the following generations the solutions are obtained by weighted linear combinations of the best solutions of the previous generation. The process is completed when convergence is achieved and the most favorable values of C_m and C_d obtained. The optimal values of drag and added mass coefficients for the case $R = 1.325 \text{ m}$, $m = 10^4 \text{ kg}$, $L = 13 \text{ m}$, $T = 8 \text{ s}$ and $A_m = 0.5 \text{ m}$ are $C_d = 0.019$ and $C_m = 1.232$. These values of C_d and C_m are obtained for a constant value of the damping coefficient $\beta = 15,28 \cdot 10^4 \text{ N s/m}$. It should be noted that this value of β is obtained as a result of an optimization process and is to be considered as an average value used only for the determination of C_d and C_m which are weakly sensitive to variations of β .

Figure 2 shows a heave motion of the PAWEC obtained by using the BEM calculation code compared to the solution based on the Morison force where $R = 1.325 \text{ m}$, $m = 10^4 \text{ kg}$, $L = 13 \text{ m}$, $T = 8 \text{ s}$, $A_m = 0.5 \text{ m}$, $\beta = 0 \text{ N s/m}$, $C_d = 0.019$ and $C_m = 1.232$.

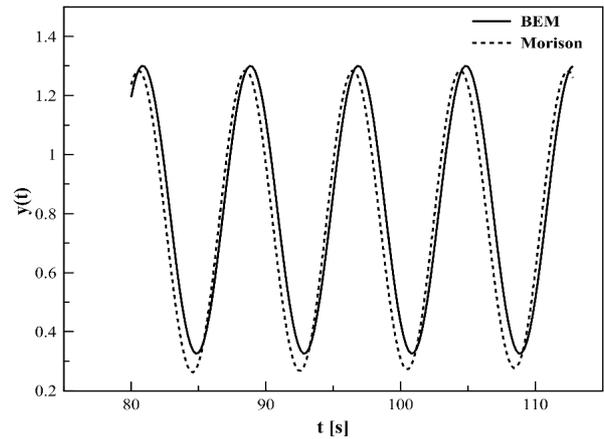


Fig. 2. Movement of the PAWEC obtained by Code NEMOH (BEM) and by using Morison equation Model

3. WEC parameters optimization

In order to maximize the energy recovered by the device, the values of the parameters of the WEC such as cylinder radius and damping coefficient of the Power Take Off device must be optimized in relation with the characteristics of the waves and the other characteristic of the device. Focusing on the role of the PTO's damping coefficient, it is necessary for damping to be as large as possible in order to maximize the energy recovery but at the same time not to be too large and restrictive for the movement of the buoy. In most cases the damping coefficient is taken as a constant, it is proposed here to consider a varying coefficient according to the speed of the buoy and this in order to allow an adaptive recovery process and thus optimizing energy recovery. The considered expression for this coefficient is given by relation (3). To determine the values of the coefficients a_i in relation (3), the energy recovery is optimized using evolutionary algorithm method (Fig. 3).

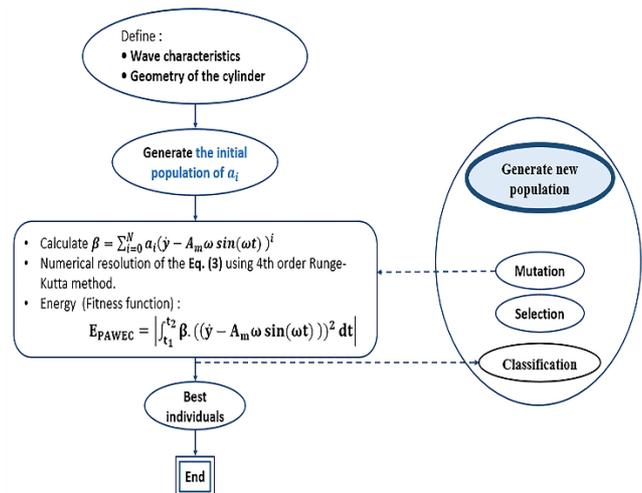


Fig. 3. Evolutionary algorithm for parametric optimization

Figure 4 illustrates the convergence of the optimization method for different values of the polynomial degree. It is noted that the convergence process is slower in the case of a variable damping coefficient, but the recovered energy is considerably increased due to the adaptation which allows the variation of damping in function of the speed.

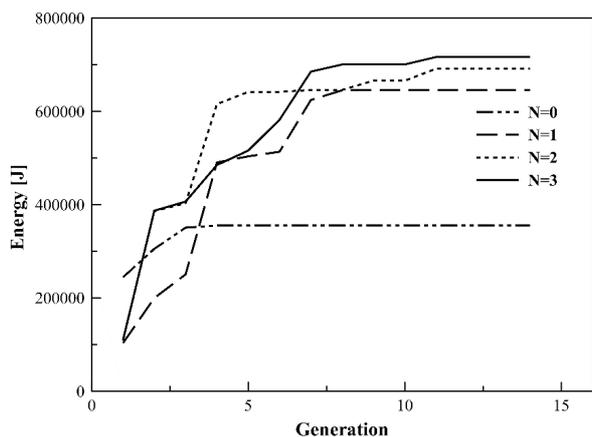


Fig. 4. Recovered energy in 7.5 period as function of generation for different values of N where $R = 1.325\text{ m}$, $m = 10^4\text{ kg}$, $L = 13\text{ m}$, $T = 8\text{ s}$, $A_m = 0.5\text{ m}$, $C_d = 0.019$ and $C_m = 1.232$.

Figure 5 presents the recovered energy during 7.5 period as function of wave amplitude for $N = 0$ and $N = 3$. In all cases ($N = 0$ and $N = 3$) the recovered energy is an increasing function of the amplitude of the wave, but the recovery is clearly more important in the case of an adaptive system.

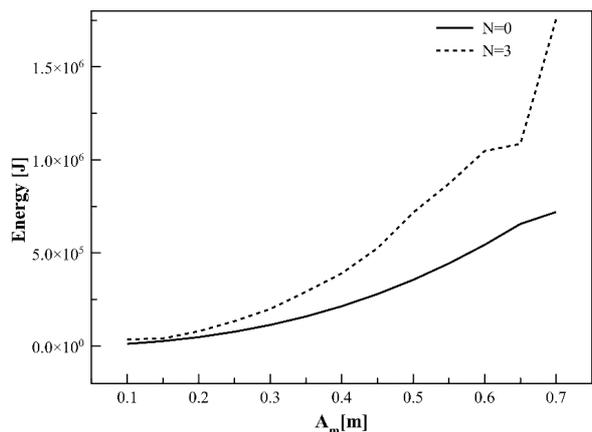


Fig. 5 Recovered energy during 7.5 period as function of wave amplitude for $N = 0$ and $N = 3$, where $R = 1.325\text{ m}$, $m = 10^4\text{ kg}$, $L = 13\text{ m}$, $T = 8\text{ s}$, $C_d = 0.019$ and $C_m = 1.232$.

In order to investigate the performance of the WEC, a coefficient named “capture width” has been introduced for the first time by Budar and Falnes [19]. It is defined as the ratio of the recovered power to the wave power. Following a similar approach, we introduce the ratio of the recovered energy by the WEC per unit length of the cylinder to the corresponding wave energy during a period of time $t_2 - t_1$, which is written as

$$\xi = \frac{E_{PAWEC}}{E_{wave}} = \frac{\int_{t_1}^{t_2} \beta(\dot{y} - A_m \omega \sin(\omega t))^2 dt}{L \rho_e g C A_m^2 (t_2 - t_1) / 2} \quad (4)$$

where L is the cylinder length and $C = \frac{\omega}{k}$ is the wave speed.

Figure 6 represents the performance of the PAWEC versus the wave amplitude with and without the adaptive

control. As shown in Figure 6, the performance of the WEC reaches a best value of 7% for wave amplitude $A_m = 0.7\text{ m}$ for $N = 3$. For all values of the wave amplitude, the PAWEC efficiency is considerably improved when a variable damping coefficient is adopted for the Power Take Off system.

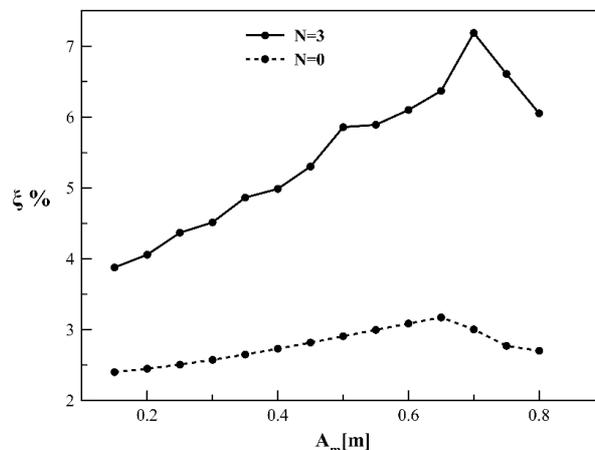


Fig. 6. Recovered coefficient in 7.5 periods as a function of wave amplitude for $N = 0$ and $N = 3$, where $R = 1.325\text{ m}$, $m = 10^4\text{ kg}$, $L = 13\text{ m}$, $T = 8\text{ s}$, $C_d = 0.019$ and $C_m = 1.232$.

4. Conclusion

This study explored the improvement of wave energy recovery systems performance by passive control methods. The goal pursued is the maximization of the energy recovery process through the adaptation of the Power Take Off device to the movement of the Buoy. The WEC considered here is of heaving point absorber type since it is widely studied, and many results are available. In contrast to the usual approaches, the method proposed here consisted in the formulation of an analytical relation linking the damping coefficient of the PTO to the powers of the relative velocity of the buoy. By optimizing the coefficients of this relation, it has been shown that the controlled variability of the PTO damping coefficient enables to increase significantly the energy recovery, by more than 100% in some cases, compared to the situation where there is no passive control or adaptation system. The mathematical model used for the different simulations is based on the Morison force that introduces added mass and drag coefficients that allow a resolution in the time domain. For parameter's optimizations, evolutionary algorithms have been used in view of their efficiency and simplicity of implementation.

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