Viscous Effects and Energy Recovery Optimization for Freely Floating and Bottom Fixed Wave Energy Converters

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Abstract- This work deals with the study of two types of wave energy converters (WEC's) taken as representative models of the bottom fixed systems and the freely floating ones. The considered freely floating WEC (FFWEC), a multi-body articulated system, consists of two horizontal cylinders connected with a flat plate and with axis parallel to the waves. The bottom fixed WEC, a point absorber (PAWEC), consists of a unique horizontal cylinder oscillating under the action of sea waves and connected to the seabed through an extensible Power Take Off device. For each system, a mathematical model is developed and is based on a balance of forces involving, in addition to the gravity and the Archimedean thrust, the Morison force, representing the added mass and damping effects as well as additional viscous effects. An evolutionary algorithm based method is used for the identification of the appropriate values of added mass and drag coefficients. The importance of the optimization of the sizing parameters for each of the systems with respect to the energy recoverable by the WEC's is shown, and an evolutionary algorithm method is also used for their optimization. For the PAWEC, the results show that the recovered energy is a decreasing function of the drag coefficient C_d and that the decay is more marked when the wave pulsation increase. This decrease remains however limited and is about 5% when C_d varies from 0 to 6. However, for the FFWEC the results show a less predictable situation as the drag coefficient increase due to the fact that the FFWEC model is more sensitive to a parameter's variation. For the FFWEC, it is found that the viscous effects can act in both directions, in favor or against a recovery of energy recovery according to the range of values of the other coefficients. It is also important to note that taking account of viscous effects can lead to corrections of more than 50% in the calculation of the energy recovered by the FFWEC.

Keywords Wave energy converter, Evolutionary algorithm, viscous effect, Heaving point absorber, freely floating WEC, Morison equation

1. Introduction

Given current energy challenges, there is a growing interest in finding new sources to extract clean and renewable energy. Although the diversity of the renewable resources, solar and wind energy are widespread and have significant investments, moreover, a variety of technologies may harvest the power stored in waves such as offshore wind farm and tidal energy [1].

In recent years, there has been a significant development in wave energy converters technologies. Drew et al. [2] introduced the general status of wave energy and evaluated device types representing wave energy converter (WEC) technology. Falcão [3] 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. Many devices have been developed or are under improvement such as PELAMIS [4] or SEAREV [5] by enhancing efficiency of systems parts such as the PTO system, the shape or several other parameters. The confrontation of various technologies, each with its strengths and weaknesses, and the comparison of their performances are useful for the current development phase of the wave energy recovery systems. Babarit et al. [6] made a comparison between eight wave energy converters with different working principles. Their objective was to estimate the mean annual power absorption of each of the eight WEC. Other reviews of these technologies are presented in Refs. [7-10].

Among the various existing devices, two large classes of WECs should be distinguished, those with ground fixations for which devices connecting the floating system to a stationary boundary area are necessary and a second class for which the WEC is freely floating and for which the energy recovery is based on a difference of motion between the parts of the floating body. The latter systems are generally articulated systems (see PELAMIS, SEAREV and WAVESTARS [11]). The freely floating devices are of particular interest insofar as they do not require expensive and complex fixing systems for their exploitation [12].

In order to test the performance of freely floating systems compared to equivalent bottom fixed systems, the present study deals with the study of two systems, one of cylindrical shape with a bottom attachment of "point absorber" type and the other one, a freely floating original system that is composed of two articulated cylinders. To make this comparison, it is assumed that the two systems have comparable volumes given the fact that the main force exploited by the wave energy converters is the Archimedean thrust, which is proportional to the volume of the floating object.

Moreover, the comparison which is carried out theoretically is based on a calculation model involving the Morison force which makes it possible to take into account the viscous damping effects that can become important in the case of the freely floating systems. In particular, in the case of articulated multi-body systems for which the energy recovery relies on the phase shift of the articulated parts rather than just the amplitude of the movements with respect to a fixed base as it is the case for the bottom-fixed systems.

The mathematical model developed in this work is based on a balance of forces involving, in addition to the gravity and the Archimedean thrust, an additional force, the Morison force, representing the added mass and damping effects. Usually, the study of floating systems is carried out on the basis of a model of non-viscous non-rotational fluid flow and by solving the fluid motion equations by numerical methods for calculating the flow potential and then the forces acting on the floating object. It is currently the model on which various numerical codes such as Wamit [13] or Nemoh [14] are based.

It should be noted that the mathematical models using the Morison equation [15] were originally developed for fully immersed bodies or for stationary objects subjected to wave action [16, 17]. However, the Morison equation has been used recently for the modeling of floating system motion as done by [18] for the modeling of floating system motion and by [19] to investigate a generic Oscillating Surge Wave Energy Converter among others. The main advantage of the Morison force approach, which will be used in this study, is to allow taking into account the viscous effects without using time consuming CFD codes.

The Morison force includes two parts, the first one is an inertia force (F_{mi}) related to the acceleration of the body and associated with the added mass coefficient C_m, the second term is the drag force (F_{md}) related to the relative velocity between the body and the fluid and associated to the drag coefficient C_d. Obtaining adequate values of coefficients C_m and C_d for a wide range of WEC's shapes and of wave parameters remains one of the difficulties associated with the use of the Morison force equation. Wolfram and Naghipour [20] discussed various methods used to analyze experimental data on the force experienced by a circular cylinder in waves to estimate drag and inertia coefficients for use in Morison's equation. Recently, Bhinder et al. [21] in a paper on the potential time domain viscous model for a surging buoy, presented a review of works concerning Morison equation coefficients and mentioned that the evaluation of the Morison force coefficients usually involves physical laboratory tests but also that some researchers have shown that computational numerical analysis can be adopted as an alternative to the experimental procedure and the force coefficients be determined thus. This last alternative is adopted in the present work, using a minimization of the gap between the solution obtained on the basis of the Morison force equation and a numerical one obtained by the boundary element method code NEMOH for the identification of the appropriate values of drag coefficients and added mass.

This paper will focus on a comparison between two WEC devices, one of freely floating type and the other of floating bottom-fixed type, with consideration of viscous effect. The considered freely floating WEC, a multi-body articulated system, consists of two cylinders connected with a flat plate. The connections between the parts of the WEC allow the rotational movements of cylinders and of the plate and the entire system perform translational movements. The bottom fixed WEC, a point absorber, consists of a unique cylinder of length L_{cy} and radius R, oscillating under the action of sea waves and connected to the seabed through an extensible Power Take Off device. In both cases, the viscous force and the pressure acting on the immerged surfaces of the cylinders are modeled by Morison's equation to which is added an Archimedes thrust and a gravity force.

To realize the comparison between the two types of systems, the bottom fixed and the freely floating one, it has already been pointed out that this comparison must be relayed at the same volume, or else considering as a significant quantity for the comparison only the energy recovered by unit of volume; in addition, the systems should be considered in their optimal function, given the imposed wave model. For this purpose, and before realizing the comparisons, each system will be subject to optimization of his characteristics by optimization methods. In this regard, optimization of wave energy converters has been the subject of several works. Banos et al. [22] presents a review of the latest numerical optimization methods used for design and control in the field of renewables energies. In their review, they mentioned that the evolutionary algorithms (E.A) are promising tools for the optimization of floating energy converters. Ringwood and Butler [23] used genetic algorithm (G.A) to optimize point absorber device that consists of a vertical cylinder moving in heave motion. Many other authors, such as [24, 25 and 26] have used genetic algorithms for WEC optimization either for WEC form parameters, for shape optimization or for the power take off systems. Following the same approach, we will use evolutionary algorithms to optimize each of the studied systems.

This paper is organized as follows: the first section is devoted to the mathematical models of the considered systems. Section two examines the identification of the drag and added mass coefficients. The third section deals with the WEC's optimization. In the fourth section, a case study analyzed the viscosity effect on the WEC's. The comparison of sensitivity to parameters variation between the two floating types of WEC's are given and discussed in the last part.

2. Mathematical Modeling

This section introduces the mathematical models for the bottom fixed heaving point absorber (PAWEC) and for the original freely floating device (FFWEC). In section 2.1, the mathematical modeling of the PAWEC is presented. Section 2.2 deals with the mathematical modeling of the FFWEC.

2.1. Bottom-fixed heaving point absorber (PAWEC).

We consider the plane motion of a cylinder of radius R in a non-inertial reference frame $\mathcal{R}(O,\vec{x},\vec{y},\vec{z})$. O is an arbitrary point taken at the moving free surface of the fluid and $\vec{y}$ is the upward vertical. The floating cylinder is connected to the sea bottom by an extensible Power Take Off device [27] and oscillating under wave's action. The position of the center O_1 is indicated by Cartesian coordinates x, y. The current paper will focus on the heave movement of the WEC, and the only degree of freedom to consider is the variable y (Fig. 1).

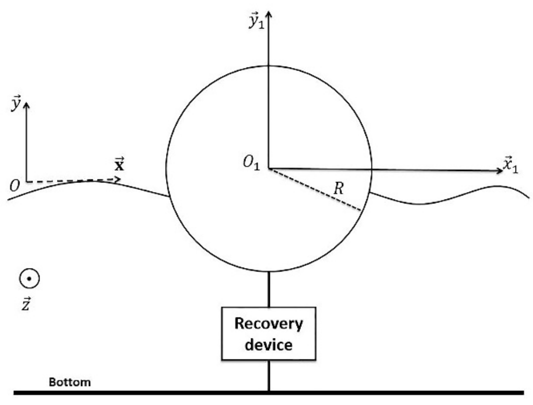


Fig. 1. Schema of the PAWEC where $\boldsymbol{\mathcal{R}}(\mathbf{O},\vec{x},\vec{y},\vec{z})$ is the reference frame linked on a point O taken arbitrarily at the free surface of the fluid and $\boldsymbol{\mathcal{R}}_1(\mathbf{O_1},\overrightarrow{x_1},\overrightarrow{y_1},\vec{z})$ is the reference frame associated to the cylinder.

In the non-inertial frame $\mathcal{R}(O,\vec{x},\vec{y},\vec{z})$, Newton's law of motion applied to the cylinder is written as:

$$m\,\ddot{y}\,\vec{y} = \vec{P} + \overrightarrow{F_m} + \overrightarrow{F_a} + \overrightarrow{F_r} - m\frac{d^2\eta}{dt^2}\vec{y} \qquad (1)$$

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, $\vec{F}_m$ is the Morison force representing the inertia and drag forces exerted by the fluid on the cylinder, $\vec{F}_a$ is the Archimedes thrust and $\vec{F}_r$ is the force exerted by the recovery system on the cylinder. The term $m\frac{d^2\eta}{dt^2}$ is an inertia force related 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, where 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 force $\vec{F}_m$ is given by the Morison equation as $\vec{F}_m = \rho_e C_m V\ddot{y}\vec{y} + \frac{1}{2}\rho_e C_d S\dot{y}|\dot{y}|\vec{y}$ where $\dot{y}$ and $\ddot{y}$ are respectively the velocity and the acceleration of the cylinder, ρ_e is the fluid density, C_m is an added mass coefficient, C_d is defined as drag coefficient, $S = RL_{cy}\,Arccos\left(\frac{y}{R}\right)$ is the wetted cross-section area of the cylinder, L_{cy} is the length of the cylinder, R is the radius and V is the volume of the body.

$\vec{F}_r$ is given by $\vec{F}_r = -\beta(\dot{y} - A_m\omega\sin(\omega t))\vec{y}$ where β is a coefficient related to the power take off device. Archimedes force is $\overrightarrow{F_a} = -\rho_e V_i\vec{g}$, where V_i is the immersed volume. By inserting the expressions of the forces in Eq. (1), one obtains the following differential equation:

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

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. Eq. (2) with initial conditions $y(t=0)$ and $\dot{y}(t=0)$, can be solved numerically by using 4th order Runge-Kutta method provided that the values of C_m and C_d are known.

2.2. Freely Floating device (FFWEC)

In a Non-inertial reference frame $\mathcal{R}(O,\vec{x},\vec{y},\vec{z})$, we consider the plane motion of an articulated multi-body system used as wave energy converter (WEC) and oscillating under the action of sea waves. The original freely floating WEC considered consists of two cylinders, of centers O_1, O_2, lengths L_1, L_2 and radius R_1, R_2 respectively, connected by a flat plate of center G and length L. The flat plate related the two cylinders on O_1 and B (Fig. 2). It is assumed that the WEC has only five degrees of freedom in the mechanical system which are the heave (y_1), the surge (x_1) and the pitch (α_1) for cylinder 1, the pitch (α_2) for cylinder 2 and the angle (α) for the plate. Here x_1, y_1 are the Cartesian coordinate of O_1 in the frame $\mathcal{R}(O,\vec{x},\vec{y},\vec{z})$, α_1 (resp. α_2) is the angle between $\vec{x}$ and $\overrightarrow{x_1}$ (resp. $\overrightarrow{x_2}$) where $\overrightarrow{x_i}$ $(i = 1,2)$ is the axis of the relative frame of reference $\mathcal{R}_i(O_i, \vec{x_i}, \vec{y_i}, \vec{z})$ attached to cylinder i and α is the angle between $\vec{x}$ and the plate O_1B.

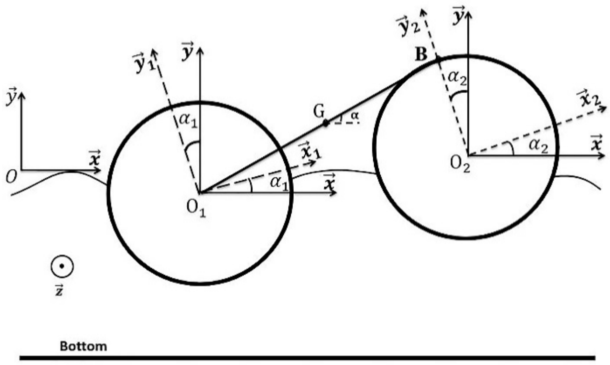


Fig. 2. Schema of the FFWEC where $\mathcal{R}(O, \vec{x}, \vec{y}, \vec{z})$ is the reference frame linked on a point O taken arbitrarily at the free surface of the fluid, $\mathcal{R}_1(O_1, \vec{x_1}, \vec{y_1}, \vec{z}))$ the reference frame associated to cylinder 1 on point O_1 and $\mathcal{R}_2(O_2, \vec{x_2}, \vec{y_2}, \vec{z}))$ the reference frame associated to cylinder 2 on point O_2.

In the non-inertial frame $\mathcal{R}(0, \vec{x}, \vec{y}, \vec{z})$, Newton's law of motion applied to each part of the system separately [cylinder 1, cylinder 2, plate] is expressed for cylinder i (i = 1 for cylinder 1 and i = 2 for cylinder 2) as follows :

$$[D_i] = [\tau_{pi}] + [\tau_{Mi}] + [\tau_{Ai}] + [\tau_{Loi}] + [\tau_{Ri}] - [\tau_{ei}] \quad (3)$$

where $[D_i]$ is the dynamic torsor, $[\tau_{pi}]$ represents the gravity force torsor, $[\tau_{Mi}]$ is the Morison force torsor representing the inertia forces and viscous forces exerted by the fluid on the system, $[\tau_{Ai}]$ is the Archimedes thrust torsor, $[\tau_{Loi}]$ represents the reactions torsor at connection between the cylinder i and the plate, $[\tau_{Ri}]$ is the forces torsor for the power take off system of the WEC and $[\tau_{ei}]$ is the inertia force torsor related to the non-inertial character of the considered reference frame. Since all the torsors are expressed at point O_i, then the terms of Eq. (3) are given by:

$$[D_i] = \begin{pmatrix} m_i\ddot{x}_i \\ m_i\ddot{y}_i \\ 0 \\ 0 \\ 0 \\ \frac{m_iR_i^2}{2}\ddot{\alpha}_i \end{pmatrix}, \ [\tau_{pi}] = \begin{pmatrix} 0 \\ -m_ig \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \ [\tau_{Mi}] = \begin{pmatrix} F_{mix} \\ F_{miy} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix},$$

$$[\tau_{Ai}] = \begin{pmatrix} F_{arix} \\ F_{ariy} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \ [\tau_{Loi}] = \begin{pmatrix} F_{ix} \\ F_{iy} \\ 0 \\ LN_i \\ M_i \\ 0 \end{pmatrix},$$

$$[\tau_{Ri}] = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\beta_i(\dot{\alpha}_i - \dot{\alpha}) \end{pmatrix}, \ [\tau_{ei}] = \begin{pmatrix} 0 \\ m_i.\frac{d^2\eta}{dt^2} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (4)$$

where m_i and R_i are respectively the mass and the radius of the cylinder i, $\ddot{x}_i$ and $\ddot{y}_i$ are the two accelerations along $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ axis respectively, $\ddot{\alpha}_i$ is the angular acceleration of the cylinder i, g represent gravity acceleration, F_{mix} and F_{miy} are given by Morison equation (Appendix A), F_{arix} and F_{ariy} are the two forces of Archimedes along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively (Appendix B), defined by $-\rho_e V_{ii} g$, where V_{ii} is the immersed volume of cylinder i, F_{ix} and F_{iy} the reaction forces at the point O_1 and B along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, LN_i and M_i the reactions momentum at the point O_1 and B along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, β_i is a coefficient related to the power take off device, $\dot{\alpha}_i$ is the angular velocity of the cylinder i and $\dot{\alpha}$ is angular velocity of the plate, $\eta(x, t)$ represent the vertical distance between a point on the free surface of the fluid and the average level of the fluid at rest.

For the plate, the Newton's second law of motion has written:

$$[D_b] = [\tau_{pb}] - [\tau_{LG_1}] - [\tau_{LG_2}] - [\tau_{eb}] \quad (5)$$

where $[D_b]$ is the dynamic torsor, $[\tau_{pb}]$ represents the gravity force torsor, $[\tau_{LG_1}]$ represents the reactions torsor at the point G between the cylinder 1 and the plate, $[\tau_{LG_2}]$ represents the reactions torsor at the point G between the cylinder 2 and the plate and $[\tau_{eb}]$ is the inertia force torsor related to the non-inertial character of the considered reference frame.
Where

$$[D_i] = \begin{pmatrix} m_b\ddot{x}_b \\ m_b\ddot{y}_b \\ 0 \\ 0 \\ 0 \\ \frac{m_bL^2}{12}\ddot{\alpha} \end{pmatrix}, \ [\tau_{pb}] = \begin{pmatrix} 0 \\ -m_bg \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \ [\tau_{LG_1}] = \begin{pmatrix} -F_{1x} \\ -F_{1y} \\ 0 \\ L_{G_1} \\ M_{G_1} \\ 0 \end{pmatrix},$$

$$[\tau_{LG_2}] = \begin{pmatrix} -F_{2x} \\ -F_{2y} \\ 0 \\ L_{G_2} \\ M_{G_2} \\ 0 \end{pmatrix}, \quad [\tau_{eb}] = \begin{pmatrix} 0 \\ m_b\frac{d^2\eta}{dt^2} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

(6)

with m_b is the mass of the plate, L is the length of the plate, $\ddot{x}_G$ and $\ddot{y}_G$ are the two accelerations along $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ axis respectively, $\ddot{\alpha}$ is the angular acceleration of the plate,

F_{ix} and F_{iy} the connection forces at the point G relative to O_1 along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, L_{G_1} and M_{G_1} the reaction moment at the point G relative to O_1 along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, F_{2x} and F_{2y} the reaction forces at the point G relative to B along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, L_{G_2} and M_{G_2} the reaction moment at the point G relative to B along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively.

By inserting the expressions of the torsors (4) and (6) in Eqs. (3) and (5), and after rearrangement, one obtains the following system of five coupled differential equations for the five degrees of freedom x_1, y_1, α, α_1 and α_2:

$$M\ddot{x}_1 - m'L\sin\alpha\,\ddot{\alpha} - m'L\cos\alpha\,\dot{\alpha}^2 + m_2R_2\cos\alpha_2\,\ddot{\alpha}_2 - m_2R_2\sin\alpha_2\,\dot{\alpha}_2^2 + F_{m1x} + F_{m2x} - F_{ar1x} - F_{ar2x} = 0 \quad (7)$$

$$M\ddot{y}_1 + m'L\cos\alpha\,\ddot{\alpha} - m'L\sin\alpha\,\dot{\alpha}^2 + m_2R_2\sin\alpha_2\,\ddot{\alpha}_2 + m_2R_2\cos\alpha_2\,\dot{\alpha}_2^2 + F_{m1y} + F_{m2y} - F_{ar1y} - F_{ar2y} + Mg = 0 \quad (8)$$

$$m''\sin\alpha\,\ddot{x}_1 - m''\cos\alpha\,\ddot{y}_1 + m'''L\ddot{\alpha} - m_2R_2\sin(\alpha - \alpha_2)\,\ddot{\alpha}_2 + m_2R_2\cos(\alpha - \alpha_2)\dot{\alpha}_2 - (F_{ar1x} - F_{ar2x})\sin\alpha + (F_{ar1y} - F_{ar2y})\cos\alpha - m''\cos\alpha\, g = 0 \quad (9)$$

$$\ddot{\alpha}_1 + \frac{2}{m_1R_1^2}\beta_1(\dot{\alpha}_1 - \dot{\alpha}) = 0 \quad (10)$$

$$m_2R_2\cos\alpha_2\,\ddot{x}_1 + m_2R_2\sin\alpha_2\,\ddot{y}_1 - m_2R_2L\sin(\alpha - \alpha_2)\,\ddot{\alpha} - m_2R_2L\cos(\alpha - \alpha_2)\,\dot{\alpha}^2 + \frac{3}{2}m_2R_2^2\ddot{\alpha}_2 + \beta_2(\dot{\alpha}_2 - \dot{\alpha}) - R_2\cos\alpha_2\,F_{ar2x} - R_2\sin\alpha_2\,F_{ar2y} + m_2R_2\sin\alpha_2\, g = 0 \quad (11)$$

where $m' = m_2 + \frac{m_b}{2}$, $m'' = m_1 - m_2$, $m''' = m_2 + \frac{m_b}{6}$ and $\mathrm{M} = m_1 + m_2 + m_b$ is the total mass of the WEC. The expressions for the Morison and Archimedes forces components are given in Appendix A and B. Numerical resolution of the coupled differential Eqs. (7)-(11) with initial conditions can be achieved by using 4th order Runge-Kutta method. However, this resolution requires knowledge of the values of added mass and drag coefficients C_m and C_d, and therefore a method of preliminary determination of these values must be adopted.

3. Determination of Added Mass and Drag Coefficients

In order to identify drag and added mass coefficients, various theoretical and experimental methods have been used [28, 29]. Yee et al. [30] used an experimental model composed of two vertical cylinders with different diameters to determine the hydrodynamics coefficients. Avila and Adamowski [31] used system identification methods to estimate drag and added mass coefficients. Recently, Jin et al. [32] show that the nonlinear viscosity should be carefully involved. An investigation into drag coefficient has been done using CFD and experimental data. The last square method has been used to compare the results obtained by CFD and the Morison model.

For the present study, for the sake to identify the drag and the added mass coefficients for a floating cylinder, a numerical solution is calculated using a code based on Boundary Element Method (BEM) and compared with the solution obtained by the Morison equation model. An evolutionary algorithm is used to generate the optimal values of the required coefficients that are minimizing the gap between the two solutions, an overview of this method can be found in [33, 34]. The objective function used for the minimization process is the sum of the squares of the gaps between the two solutions $E_{rr} = \sum\left(y_{Nemoh}(i) - y_{Morison}(i)\right)^2$.

The first generation used for the evolutionary algorithm is obtained by random drawing of the values, for the following generations a cross of the best solutions is operated by weighted linear combinations of the best solutions of the previous generation.

Fig. 3 shows the sum of the squares of the gaps between the two solutions as a function of the number of generations. It can be seen in Fig. 3 that E_{rr} is a decreasing function of the generation number. For the considered values of $R = 0.10125\,m$, $m = 11.7\,kg$, $L_{cy} = 1.1\,m$, $T = 4\,s$ and $A_m = 0.06\,m$ the optimal values of added mass and drag coefficients are found to be $C_m = 7.46$ and $C_d = 0.61$.

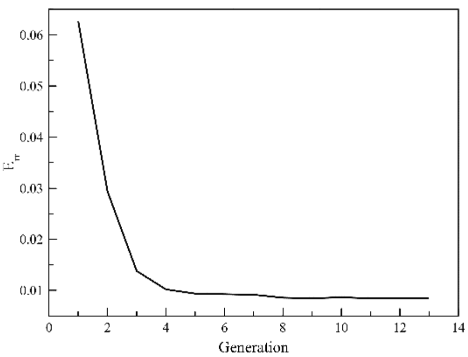


Fig. 3. The sum of the squares of the gaps between the two solutions as a function of the number of generation.

Fig. 4 shows a heaving motion of the PAWEC obtained using the NEMOH calculation code and then using a model based on the Morison force where $R = 0.10125\,m$, $m = 11.7\,kg$, $L_{cy} = 1.1\,m$, $T = 4\,s$, $A_m = 0.06\,m$, $C_d = 0.61$ and $C_m = 7.46$. It is found that the motion is correctly reproduced when using the Morison model, and that this model allows with simplified calculations to determine the motion of a floating object taking into account the main effects of added mass and damping.

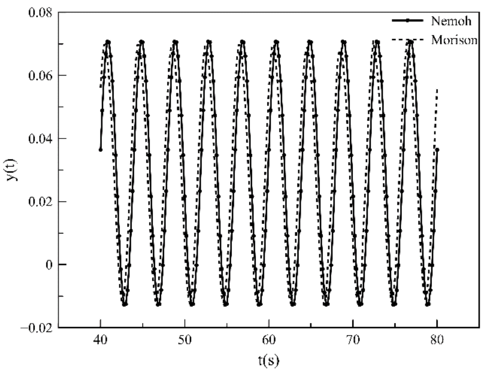


Fig. 4. Heaving motion of the PAWEC obtained by BEM code Nemoh and Morison equation Model.

4. WEC's Parameters Optimization

The optimization of wave energy converters has been discussed by many researches. Among the used methods, there is the evolutionary algorithm.

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. In our case, an evolutionary algorithm based code, presented on Fig. 5, is used to optimize the system parameters. The first case is to optimize the PAWEC by determining the optimal value of the coefficient of the Power Take Off device. The second case is realized to find the optimal values of the damping coefficients of the FFWEC.

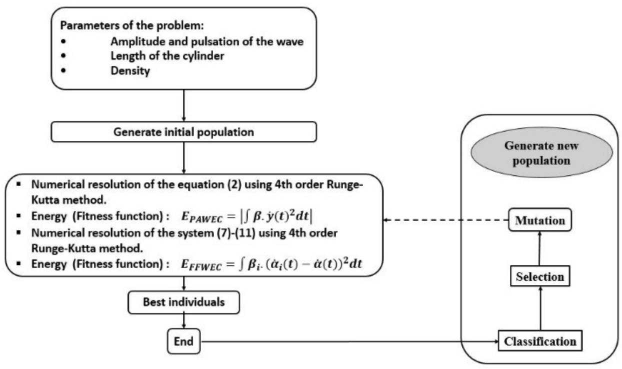


Fig. 5. Evolutionary algorithm for parametric optimization.

4.1. PAWEC Optimization

The energy recovered by PAWEC is obtained by:

$$E = \left| \int_{t_1}^{t_2} \beta \dot{y}^2(t)\, dt \right| \tag{12}$$

where t_1 and t_2 are the times of integration.

It is found that there is a value of the recovery coefficient that maximizes the recovered energy. In fact, insofar as the energy recovery is achieved through a friction force, it is clear that by increasing this friction force, the amplitude of the movements of the float is reduced, and that at the limit an excessive friction will lead to complete braking of the movement of the float and thus will cancel the recovery of energy. Therefore, there exists between the two limits of zero friction and excessive friction an optimal value of the friction which maximizes the energy recovered and this is what is identified in Fig. 6. This figure presents the recovered energy during 3.75 wave period T by PAWEC as a function of the coefficient of the Power Take Off device β, where $R = 0.10125\, m$, $A_m = 0.06m$ and $T = 4\, s$. It shows that the recovered energy increase until an optimum value of $E = 36.253\, J$ for a coefficient of PTO device $\beta = 900\, Ns/m$.

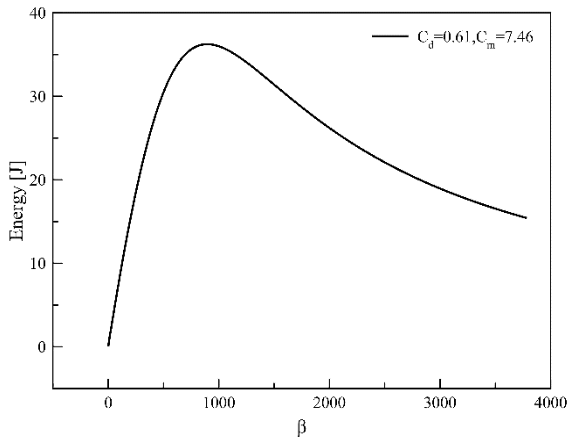


Fig. 6. The energy recovered by PAWEC as a function of the PTO device coefficient β.

4.2. PAWEC Optimization

The energy recovered by the cylinder *i* is:

$$E_i = \left| \int_{t_1}^{t_2} \beta_i (\dot{\alpha}_i(t) - \dot{\alpha}(t))^2\, dt \right| \tag{13}$$

and the energy recovered by FFWEC is the sum of the energy recovered by the two cylinders, such as :

$$E = E_1 + E_2 \tag{14}$$

Fig. 7 illustrates the recovered energy by FFWEC in 3.75 periods as a function of the Power Take Off device coefficients β_1 and β_2, where $R_1 = R_2 = 0.0716\, m$, $A_m = 0.06m$, $T = 4s$ and $L = 0.22584\, m$. The optimum recovered energy is E=104.3 J for the coefficients of PTO device $\beta_1 = 0.2\, Ns/m$ and $\beta_2 = 0.65\, Ns/m$. It should be noted that the energy recovered by the cylinders 1 and 2 are respectively $E_1 = 53.15$ J and $E_2 = 51.15$ J. For the sake to analyze the effect of the PTO coefficients on the recovered energy, a fixed value of β_1 was given to $20\, Ns/m$ in order to optimize β_2 and L. It is found in this case that $\beta_2 = 0.4\, Ns/m$ and $L = 0.35\, m$ are the optimum values while the recovered energy is $E = 69.3265\, J$. In this situation, the energy recovered by the cylinders 1 and 2 are respectively $E_1 = 0.08$ J and $E_2 = 69.246$ J.

Optimization of the parameters β_1, β_2 and L has been investigated using an evolutionary algorithm method. The optimal recovered energy is $E = 103.8\,J$ where the best values of the parameters are $\beta_1 = 0.29298$ Ns/rad, $\beta_2 = 0.66129$ Ns/rad and $L = 0.22584\,m$.

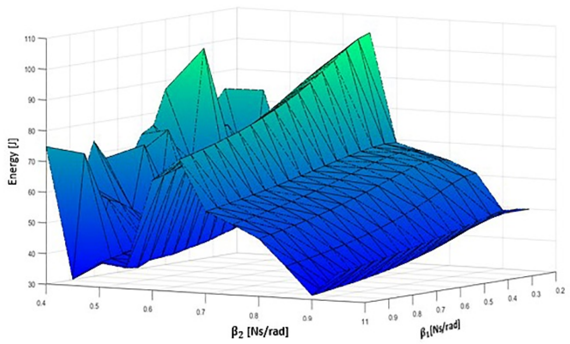


Fig. 7. The recovered energy by FFWEC as a function of the PTO coefficients β_1 and β_2.

5. Viscous Effect on WEC'S

In order to clarify the effects of viscous friction on the energy recovery capacities of floating systems, computational methods require at least the introduction of an unsteady boundary layer in the vicinity of the object, or a complete resolution by a 3D numerical calculation code that can become expensive in terms of calculation time. One of the possibilities offered by Morison's force-type model, which remains fairly simple, is the possibility of taking into account additional drag forces by varying the drag coefficient in the Morison force expression

This last approach is the one that we propose to use to simulate, in a first approximation, viscosity effects. These effects, which a priori are of the "resistive" type corresponding to a loss of energy, may in certain cases be useful for the process of energy recovery by the floating system.

Let us first note that in the Morison force expression there are two parts, a first part is the force related to the effects of added mass, and is proportional to the relative acceleration between the floating system and the fluid, and a second part proportional to the square of the relative speed and which represents both damping effects and viscous effects.

The magnitude of the viscous forces is related to the Keulegan-carpenter number [35]. As mentioned by Laya et al. [36], Keulegan and Carpenter postulated that the harmonic fluid forces on a cylinder are, in general, functions of Reynolds number, Re, and a nondimensional "period" parameter proportional to the ratio of drag and inertia forces, KC, called the Keulegan-Carpenter number and defined as:

$$KC = \frac{U_m T_f}{D}$$

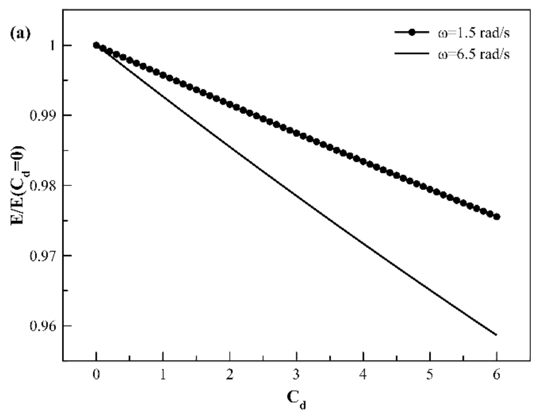
where U_m is the sinusoidal velocity amplitude, T_f is the sinusoidal velocity period and D is the cylinder diameter. For deep water waves, the KC number can be re-written as

$$KC = \frac{2\,\pi\,A_m}{D}$$

where A_m is the amplitude of the wave. In the case of low damping effects, an increase in the drag coefficient even by 100% only slightly impacts the system. On the other hand, in the case where damping effects are important in front of the inertia effects, a variation of C_d can causes more important modifications on the movements of the floats and thus on the energy recovery process.

Fig. 8.a shows the ratio of the recovered energy (E) to a reference value of recovered energy calculated for $C_d = 0$ for the PAWEC and the FFWEC as a function of drag coefficient C_d in two cases: case (i) the inertia force is more significant than the drag force where $\omega = 1.5\,rad/s$, case (ii) the drag force is larger than the inertia force where $\omega = 6.5\,rad/s$. It should be noted that in both cases WEC's parameters are set to optimum values.

The result shows that the PAWEC's recovered energy is a decreasing function of the drag coefficient C_d (Fig. 8.a) and that the decay is more marked when the wave pulsation increase. This decrease remains however limited and is about 5% when C_d varies from 0 to 6. However, for the FFWEC the results show a less predictable situation as the drag coefficient increase in case (i) and in case (ii) (Fig. 8.b), this is probably due to the fact that the FFWEC model is more sensitive to a parameter's variation. It is found that the viscous effects can act in both directions, in favor or against a recovery of energy recovery according to the range of values of the other coefficients. It is also important to note that taking account of viscous effects can lead to corrections of more than 50% in the calculation of the energy recovered by the FFWEC.



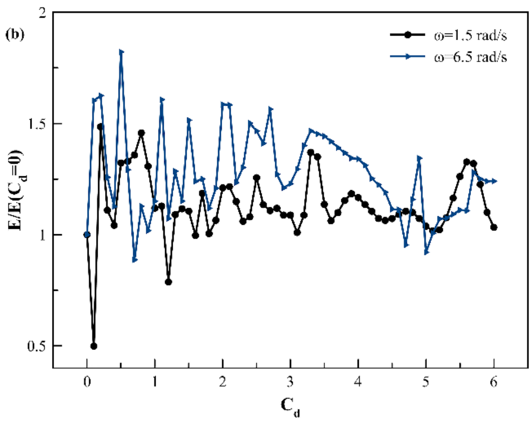


Fig. 8. Recovered energy by (a) PAWEC and (b) FFWEC as a function of drag coefficient.

6. Comparison of Sensitivity to Parameters Variation

The comparison between the two systems considered can be essentially based on the energy recovered by each of the systems when it is dimensioned optimally. The obtained results show that, in the considered cases, the freely floating system FFWEC can be quite efficient and recover more energy than the PAWEC system under specific conditions. However, articulated multibody systems like the FFWEC are very sensitive to parameter variations, and it should be emphasized that the theoretical design values that maximize the recovered energy cannot be strictly maintained in a real-life situation, particularly in terms of wave characteristics. Indeed, the waves are very variables in their characteristics and the regularity of the expressions used to represent them constitute only theoretical approximations. Therefore, it is necessary to study the behavior of energy recovery systems in case of fluctuation of the values of the parameters around their nominal values.

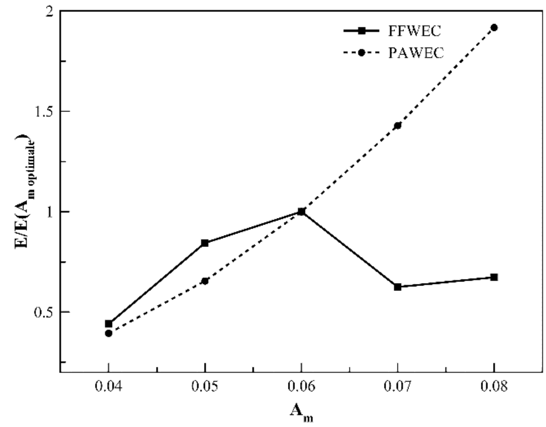


Fig.9. The recovered energy by FFWEC and PAWEC as a function of the wave amplitude.

Fig. 9 shows the ratio between the recovered energy and the recovered energy in the optimum case where $A_m = 0.06\ m$, $R_1 = R_2 = 0.0716\ m$ and $R = 0.1025\ m$ by the two WEC's. It is noted that in the case of PAWEC the behavior is stable and that a small variation of amplitude of the waves induces a quasi-proportional variation of the recovered energy. On the other hand, in the case of FFWEC, a slight deviation in the values of the parameters can lead to a significant drop in the energy recovered. Similar behavior is observed when the recovery coefficients are varied (Figs. 10.a-b).

Figs. 10.a and 10.b show the variations of the energy recovered by the FFWEC in the case where one of the PTO coefficients is varied while the other is maintained at a constant value. We note that the recovered energy varies by more than 50% when the coefficients are modified.

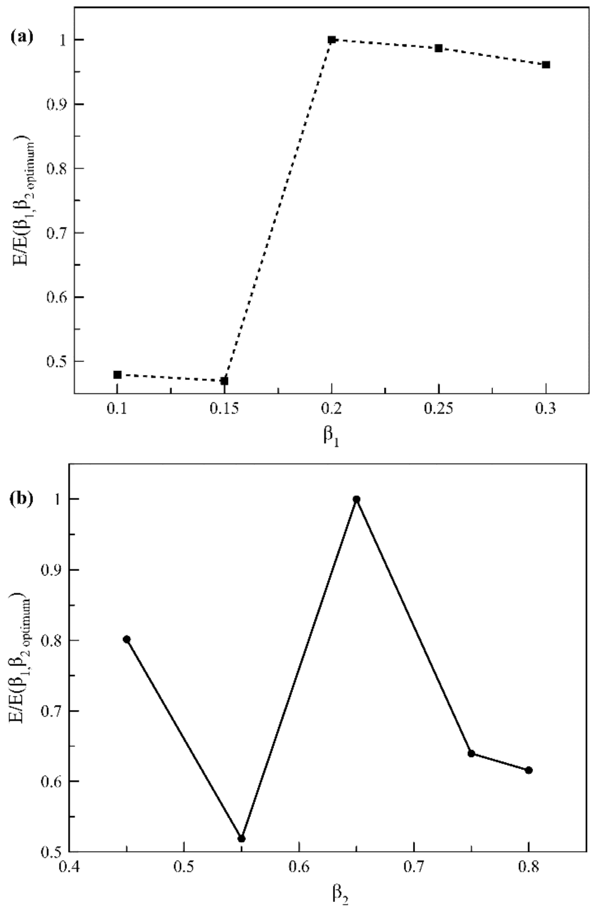


Fig.10. The recovered energy by FFWEC as a function of the PTO coefficients β_1 and β_2 : (a) $\beta_{2,optimum} = 0.65\ Ns/rad$, (b) $\beta_{1,optimum} = 0.2\ Ns/rad$.

7. Conclusion

The current study present and investigate an original floating WEC and a heaving point absorber WEC. A parametric optimization has been done to improve the recovered energy by the two WEC's. As a case study, it is found that the viscous effects can act in both directions, in favor or against a recovery of energy recovery according to the range of values of the other coefficients. It is noted that the adding of viscous drag coefficient can improve the recovered energy by the FFWEC by 50%.

The obtained results show that, in the considered cases, the freely floating system FFWEC can be quite efficient and recover more energy than the PAWEC system under specific conditions. However, articulated multibody systems like the FFWEC are very sensitive to parameter variations, and it should be emphasized that the theoretical design values that maximize the recovered energy cannot be strictly maintained in a real-life situation, particularly in terms of wave characteristics.

Appendix A. Morison Force

The expression of Morison equation along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively written as:

$$F_{mix} = \rho_e C_m V_{ii} \ddot{x}_i + \frac{1}{2}\rho_e C_d S_i \dot{x}_i |\dot{x}_i| \quad (A.1)$$

$$F_{miy} = \rho_e C_m V_{ii} \ddot{y}_i + \frac{1}{2}\rho_e C_d S_i \dot{y}_i |\dot{y}_i| \quad (A.2)$$

where $\dot{x}_i$ and $\ddot{x}_i$ are respectively the velocity and the acceleration of the cylinder *i* along $\overrightarrow{Ox}$, $\dot{y}_i$ and $\ddot{y}_i$ are respectively the velocity and the acceleration of the cylinder *i* along $\overrightarrow{Oy}$, ρ_e represent fluid density, C_m represent added mass coefficient, C_d is defined as drag coefficient, $S_i = R_i L_i \arccos\left(\frac{y_i}{R_i}\right)$ is the wetted cross-section area of cylinder perpendicular to the direction of flow, L_i is the length of the cylinder *i*, V_{ii} is the immersed volume of the cylinder *i*.

Appendix B. Archimedes Force

The expression of the Archimedes force along the axis $\overrightarrow{Ox}$ is given by:

$$F_{ar1x} = \rho_e g L_1 R_1 y_1 \left(\sin\left(\theta_L + \frac{\eta_1}{R_1}\right) + \sin\left(\theta_L + \frac{\eta_2}{R_1}\right)\right) - \frac{\rho_e g L_1 R_1^2}{4}\left(\cos\left(2\left(\theta_L + \frac{\eta_1}{R_1}\right)\right) - \cos\left(2\left(\theta_L + \frac{\eta_2}{R_1}\right)\right)\right) \quad (B.1)$$

$$F_{ar2x} = \rho_e g L_2 R_2 (y_1 + L sin(\alpha) - R_2 cos(\alpha_2))\left(sin\left(\theta_{L2} + \frac{\eta_3}{R_2}\right) + sin\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right) - \frac{\rho_e g L_2 R_2^2}{4}\left(cos\left(2\left(\theta_{L2} + \frac{\eta_3}{R_2}\right)\right) - cos\left(2\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right)\right) \quad (B.2)$$

The Archimedes force along the axis $\overrightarrow{Oy}$ written as:

$$F_{ar1y} = -\rho_e g L_1 R_1 y_1 \left(sin\left(\theta_L + \frac{\eta_1}{R_1}\right) + sin\left(\theta_L + \frac{\eta_2}{R_1}\right)\right) + \rho_e g L_1 R_1^2 \left(\theta_L + \frac{\eta_1+\eta_2}{2R_1} + \frac{1}{4}\left(sin\left(2\left(\theta_L + \frac{\eta_1}{R_1}\right)\right) + sin\left(2\left(\theta_L + \frac{\eta_2}{R_1}\right)\right)\right)\right) \quad (B.3)$$

$$F_{ar2y} = -\rho_e g L_2 R_2 (y_1 + L sin(\alpha) - R_2 cos(\alpha_2))\left(sin\left(\theta_{L2} + \frac{\eta_3}{R_2}\right) + sin\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right) + \rho_e g L_2 R_2^2 \left(\theta_{L2} + \frac{\eta_3+\eta_4}{2R_2} + \frac{1}{4}\left(sin\left(2\left(\theta_{L2} + \frac{\eta_3}{R_2}\right)\right) + sin\left(2\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right)\right)\right) \quad (B.4)$$

where L_1 and L_2 are [22] the cylinder 1 and the cylinder 2 respectively, R_1 and L_2 are the radius of the cylinder 1 and the cylinder 2 respectively, g represent gravity acceleration, ρ_e is the fluid density and L is the length of the plate.
with:

$\theta_L = arcos\left(\frac{y_1}{R_1}\right)$, $\theta_{L2} = arcos\left(\frac{y_1 + Lsin(\alpha) - R_2 cos(\alpha_2)}{R_2}\right)$,
$\eta_1 = A_m \cos(\omega t - k(x_1 - R_1 sin\theta_L))$,
$\eta_2 = A_m \cos(\omega t - k(x_1 + R_1 sin\theta_L))$,
$\eta_3 = A_m \cos(\omega t - k(x_1 + Lcos\alpha + R_2 sin\alpha_2 - R_2 sin\theta_{L2}))$,
$\eta_4 = A_m \cos(\omega t - k(x_1 + Lcos\alpha + R_2 sin\alpha_2 + R_2 sin\theta_{L2}))$,

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