WEC PARAMETERS OPTIMIZATION BY GENETIC ALGORITHM METHOD
MARINE 2017

A.JABRALI[1], R.KHATYR[2] AND J.KHALID NACIRI[3]
Laboratory of Mechanics, Faculty of Sciences Aïn Chock, B.P 5366, Maarif
Hassan II University, Casablanca, Morocco
Corresponding authors: E-Mail: ([1]) jabraliahmed10@gmail.com
([2]) khatyrrabha@gmail.com
([3]) naciriuh2c@gmail.com

Key words: Genetic algorithm, parameters optimization, floating WEC, multi-body articulated system

Abstract. This study presents a method for parameters optimization for a floating wave energy converter (WEC) device. The considered 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. This study focuses on the case of two-dimensional movements of the WEC due to the action of waves which propagate perpendicular to the axis of the cylinders. The pressure and the viscous forces acting on the wetted surfaces of the cylinders are modeled by the Morison force equation [10], to which are added Archimedes and gravity forces.

The Newton laws written for the multi-body articulated system, whose movements have five degrees of freedom, result in a system of five nonlinear second-order differential equations which is solved numerically by a fourth order Runge-Kutta method [11]. The results show the effects of various parameters as the radius of the cylinders, the length of the relating plate, the coefficients of the power take off device, and the wave characteristics on the efficiency of the wave energy converter. To optimize these parameters values, we use a genetic algorithm method [7] for determination of optimal values. The first test of the method is an optimization of the power recovery coefficients for fixed values of geometric WEC parameters and of the wave characteristics. Thereafter, the genetic algorithm method is used to optimize various WEC parameters.

1 INTRODUCTION

Many wave energy recovery technologies have been developed in recent decades. A review of these technologies can be found in the refs. [1-3]. Among the various existing devices, the floating devices are of particular interest insofar as they do not require costly and complex fixing systems for their exploitation. High performance floating energy recovery devices such as PELAMIS [4], or SEAREV [5] systems are undergoing extensive work and are continually being improved by addressing key factors such as power recovery systems (PTO), shapes used, and other parameters.

The optimization of all the characteristic parameters of these systems is of great interest for their future development. Banos *et al.* [6] presents a review of numerical optimization methods used in the field of renewable energies. Genetic algorithms are tools which are promising for the optimization of floating energy converters insofar as they make it possible to envisage, at least at the theoretical level, an overall optimization of the device by acting on both the shapes and the characteristic parameters of the system in terms of magnitude and this in relation to the waves to which the converter is exposed.

This approach was adopted by Babarit *et al.* [7] who used the genetic algorithm to optimize the shape and mechanical parameters of the SEAREV device in order to maximize the annual production of energy at a given site. Similarly, McCabe *et al.* [8] studied the optimization of the shape of a wave energy collector to improve energy extraction using genetic algorithms. Recently, Zhang *et al.* [9] studied a multi-pendulum energy converter. The final structural parameters of the pendulum were obtained using a genetic algorithm based on the results of the numerical simulation of the pendulum structure.

This study presents a method for parameters optimization for a floating wave energy converter (WEC) device. The considered 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. This study focuses on the case of two-dimensional movements of the WEC due to the action of waves which propagate perpendicular to the axis of the cylinders.

The pressure and the viscous forces acting on the wetted surfaces of the cylinders are modelled by the Morison force equation [10], to which are added Archimedes and gravity forces.

The Newton laws written for the multi-body articulated system, whose movements have five degrees of freedom, result in a system of five nonlinear second-order differential equations governing the motion of the WEC which is solved numerically by a fourth order Runge-Kutta method [11]. The results show the effects of various parameters as the radius of the cylinders, the length of the relating plate, the coefficients of the power take off device, and the wave characteristics on the efficiency of the wave energy converter. To optimize these parameters values, we use a genetic algorithm method for determination of optimal values. The first test of the method is an optimization of the power recovery coefficients for fixed values of geometric WEC parameters and of the wave characteristics. Thereafter, the genetic algorithm method is used to optimize various WEC parameters.

2 MATHEMATICAL MODELING

In a Non-inertial reference frame $\mathcal{R}(0,\vec{x},\vec{y},\vec{z})$, where O is an arbitrary point taken at the moving free surface of the fluid and $\vec{y}$ is the upward vertical, 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 WEC consists of two cylinders, of centers O_1 and O_2 and radius R_1 and R_2 respectively, connected by a flat plate of center G and length L. Taking into account the connections between parts of the system as shown in figure 1, and since only plane movements of the WEC are considered, we introduce five degrees of freedom for 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 $\mathcal{R}(0,\vec{x},\vec{y},\vec{z})$, 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 $\mathcal{R}_i(0_i,\overrightarrow{x_i},\overrightarrow{y_i},\vec{z})$ attached to cylinder i and α is the angle between $\vec{x}$ and the plate O_1B.

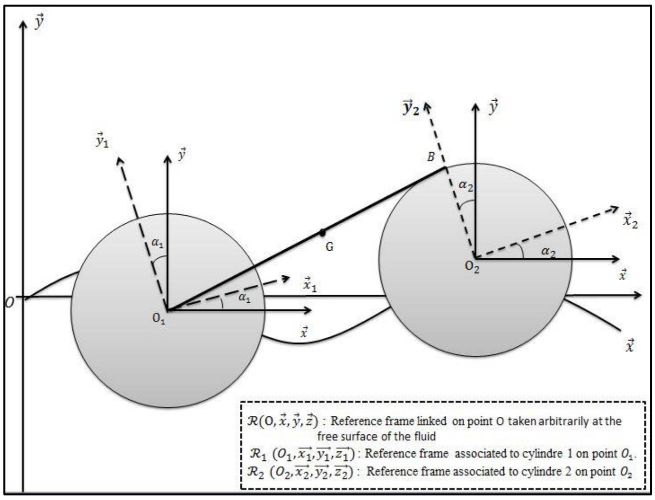

Figure 1: Schema of the floating system

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 :

$$[D_i] = [\tau_{pi}] + [\tau_{Mi}] + [\tau_{Ai}] + [\tau_{Loi}] + [\tau_{Ri}] - [\tau_{ei}] \quad (1)$$

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 equation (1) are given by:

$$[D_i] = \begin{pmatrix} m_i\ddot{x}_i \\ m_i\ddot{y}_i \\ 0 \\ 0 \\ 0 \\ \frac{m_i R_i^2}{2}\ddot{\alpha}_i \end{pmatrix}, \left[\tau_{pi}\right] = \begin{pmatrix} 0 \\ -m_i g \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, [\tau_{Mi}] = \begin{pmatrix} F_{mix} \\ F_{miy} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, [\tau_{Ai}] = \begin{pmatrix} F_{arix} \\ F_{ariy} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix},$$

$$[\tau_{Loi}] = \begin{pmatrix} F_{ix} \\ F_{iy} \\ 0 \\ L_i \\ M_i \\ 0 \end{pmatrix}, [\tau_{Ri}] = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\beta_i(\dot{\alpha}_i - \dot{\alpha}) \end{pmatrix}, [\tau_{ei}] = \begin{pmatrix} 0 \\ m_i.\frac{d^2\eta}{dt^2} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Were m_i is the mass 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 acceleration of gravity, F_{mix} and F_{miy} are given by Morison equation [10], F_{arix} and F_{ariy} are the two forces of Archimedes along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, defined by $-\rho_e V_{ii} g$, where V_{ii} is the immersed volume, F_{ix} and F_{iy} the reaction forces at the point O_1 and B along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, $L_i$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 the damping coefficients related to the power take off devices, $\dot{\alpha}_i$ is the angular velocity of the cylinder i and $\dot{\alpha}$ is angular velocity of the plate, η represent the distance between the assumed flat bottom and the free surface.

For the plate the Newton's second law of motion is written as:

$$[D_b] = \left[\tau_{pb}\right] - [\tau_{LG1}] - [\tau_{LG2}] - [\tau_{eb}] \quad (2)$$

Where $$[D_i] = \begin{pmatrix} m_b\ddot{x}_b \\ m_b\ddot{y}_b \\ 0 \\ 0 \\ 0 \\ \frac{m_b R_b^2}{12}\ddot{\alpha} \end{pmatrix}, \left[\tau_{pb}\right] = \begin{pmatrix} 0 \\ -m_b g \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, [\tau_{LG1}] = \begin{pmatrix} -F_{1x} \\ -F_{1y} \\ 0 \\ L_{G1} \\ M_{G1} \\ 0 \end{pmatrix}, [\tau_{LG2}] = \begin{pmatrix} -F_{2x} \\ -F_{2y} \\ 0 \\ L_{G2} \\ M_{G2} \\ 0 \end{pmatrix}, [\tau_{eb}] = \begin{pmatrix} 0 \\ m_b.\frac{d^2\eta}{dt^2} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

with η represent the distance between the assumed flat bottom and the free surface, m_b is the mass 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, $F_{1x}$and F_{1y} the connection forces at the point G relative to O_1 along the axis $\overrightarrow{Ox}$ and $\overrightarrow{Oy}$ respectively, L_{G1} and M_{G1} 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_{G2} and M_{G2} 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 in equations (1) and (2), and after a rearrangement, we obtain the following system of five coupled differential equations for the five degrees of freedom x_1, y_1, α, α_1 and α_2:

$$M\ddot{x}_1 - m'L\sin\alpha\,\ddot{\alpha} - m'L\cos\alpha\,\dot{\alpha}^2 + m_2R_2\cos\alpha_2\,\ddot{\alpha}_2 - m_2R_2\sin\alpha_2\,\dot{\alpha}_2^2 + F_{m_1x} + F_{m_2x} - F_{ar_1x} - F_{ar_2x} = 0 \tag{3}$$

$$M\ddot{y}_1 + m'L\cos\alpha\,\ddot{\alpha} - m'L\sin\alpha\,\dot{\alpha}^2 + m_2R_2\sin\alpha_2\,\ddot{\alpha}_2 + m_2R_2\cos\alpha_2\,\dot{\alpha}_2^2 + F_{m_1y} + F_{m_2y} - F_{ar_1y} - F_{ar_2y} + Mg = 0 \tag{4}$$

$$m''\sin\alpha\,\ddot{x}_1 - m''\cos\alpha\,\ddot{y}_1 + m'''L\ddot{\alpha} - m_2R_2\sin(\alpha-\alpha_2)\,\ddot{\alpha}_2 + m_2R_2\cos(\alpha-\alpha_2)\dot{\alpha}_2 - \left(F_{ar_1x} - F_{ar_2x}\right)\sin\alpha + \left(F_{ar_1y} - F_{ar_2y}\right)\cos\alpha - m''\cos\alpha\, g = 0 \tag{5}$$

$$\ddot{\alpha}_1 + \frac{2}{m_1R_1^2}\beta_1(\dot{\alpha}_1 - \dot{\alpha}) = 0 \tag{6}$$

$$m_2R_2\cos\alpha_2\,\ddot{x}_1 + m_2R_2\sin\alpha_2\,\ddot{y}_1 - m_2R_2L\sin(\alpha-\alpha_2)\,\ddot{\alpha} - m_2R_2L\cos(\alpha-\alpha_2)\,\dot{\alpha}^2 + \frac{3}{2}m_2R_2^2\ddot{\alpha}_2 + \beta_2(\dot{\alpha}_2 - \dot{\alpha}) - R_2\cos\alpha_2\,F_{ar_2x} - R_2\sin\alpha_2\,F_{ar_2y} + m_2R_2\sin\alpha_2\, g = 0 \tag{7}$$

Where $\mathrm{M} = m_1 + m_2 + m_b$ is the total mass of the WEC. Relations expressing Archimedes and Morison forces components are given in appendix 1. The numerical resolution of the coupled differential equations (3)-(7) is achieved by using 4th order Runge-Kutta method.

3 GENETIC ALGORITHM

In order to maximize the energy recovered by the device, the values of the characteristic parameters of the device such as the length of the plate and the damping coefficients of the power take off system are determined as functions of the characteristics of the waves. A genetic algorithm based code, presented in (Figure 2), is used to optimize the system. First test has been realized for the determination of the optimal values of the damping coefficients by leaving fixed the values of cylinder radius and wave characteristics and a comparison between the results obtained by genetic algorithm method and those of a direct calculation of optimal values are achieved. After this validation tests, the damping coefficients and other parameters of the WEC geometry are determined in order to optimize the energy recovering.

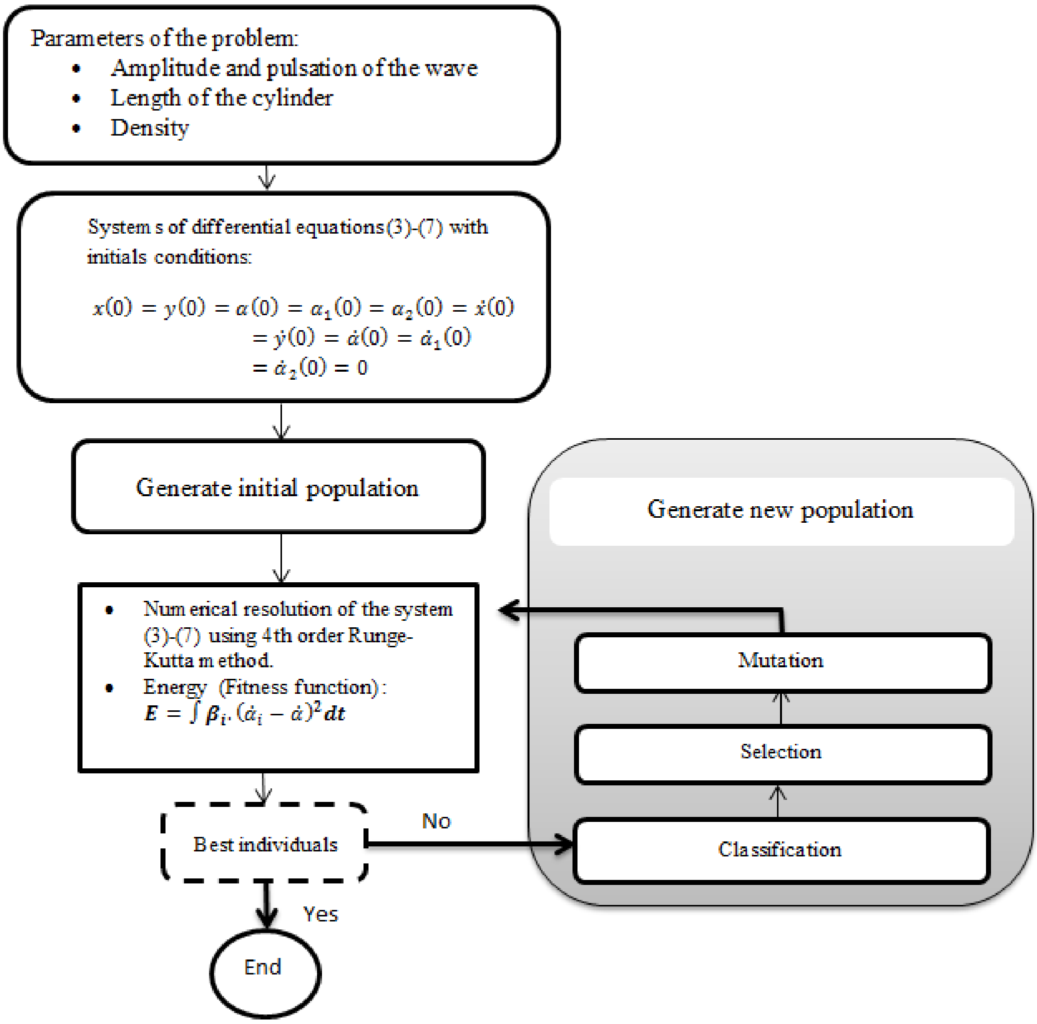

Figure 2: Genetic algorithm for parametric optimization

4 RESULTS AND DISCUSSION

Figure 3 presents the direct calculation of the energy recovered for one period, depending to the coefficients β_1 and β_2 of the power take off devices of cylinder 1 and cylinder 2. It is noted that recovered energy increases up to optimum values of the two coefficients of PTO devices β_1 and β_2.

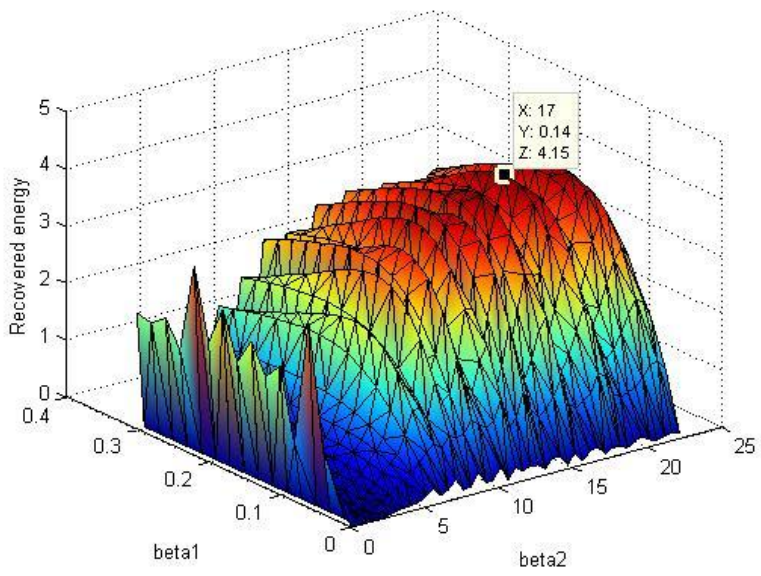

Figure 3: The energy recovered depending to the PTO devices coefficients β_1 and β_2.

Figure 4 presents the convergence process for the genetic algorithm (G.A) method by plotting the best energy recovered at each generation versus the number of generations. In this case one presents the optimization of the parameters β_1 and β_2 of the PTO device where $R_1 = R_2 = 0.057m \; and \; L = 0.15m$. It is noted that the optimal values of $\beta_1$and β_2 obtained by G.A and by the direct calculation method are in close agreement (table 1). The advantage of using genetic algorithm method is to reduce the computer calculation time (see table 1).

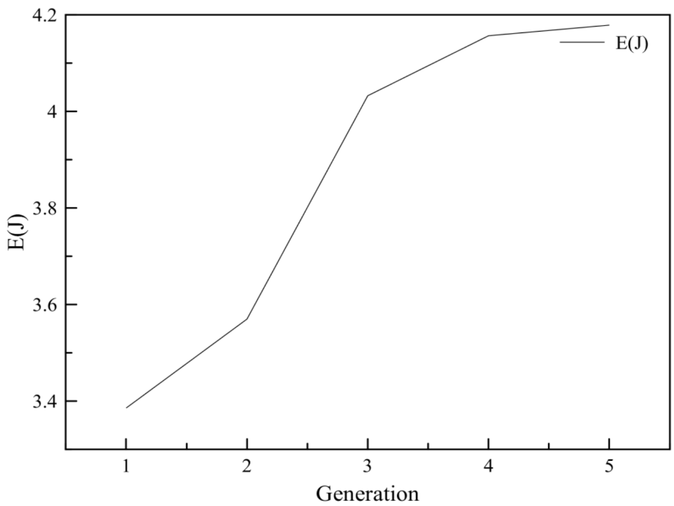

Figure 4: The energy recovered depending to the generation.

Table 1 : Time of calculation and recovered energy on one period**.**

	β_1 optimum	β_2 optimum	Energy (J)	Time of calculations (s)
G.A	0.121	17.1	4.17	27000
Direct calculation	0.14	17	4.15	83056

In the second test, we optimized by GA method the parameters β_1, β_2 and L in situation where $A_m = 0.02\,m, \omega = 0.2\,rad/s\ and\ R_1 = R_2 = 0.057m$, the results are satisfactory. It is noted that the new value of L=0.16 obtained by G.A increase the recovered energy to the value of 4.19J.

REFERENCES

[1] António, F. and Falcão de, O. Wave energy utilization: A review of the technologies. Renewable and sustainable energy reviews (2010) **14:** 899–918.

[2] Thorpe, T. W. A brief review of wave energy, Technical report. N° ETSU-R120, Energy Technology Support Unit (ETSU), a report produced for the UK Department of Trade and Industry (1999).

[3] Clément, A., McCullen, P., Falcão, A., Fiorentino, A., Gardner, F., Hammarlund, K., Lemonis, G., Lewis, T., Nielsen, K., Petroncini, S., Pontes, M.T., Schild, P., Sjöström, B.O., Sørensen, H.C. and Thorpe T. Wave energy in Europe: current status and perspectives. Renew Sustain Energy Rev. (2002) **6**: 405–431.

[4] Carcas, M. The OPD Pelamis WEC: current status and onward programme (2002). Int. J. Ambient Energy (2003) **24** : 21–28.

[5] Gilloteaux J.C. Mouvements de grande amplitude d'un corps flottant en fluide parfait : application à la récupération de l'énergie des vagues, Thèse de doctorat, École Centrale de Nantes, Université de Nantes (2007).

[6] Banos, R., Manzano-Agugliaro, F., Montoya, F.G., Gil, C., Alcayde, A. and Gómez, J. Optimization methods applied to renewable and sustainable energy: Renewable and Sustainable Energy Reviews (2011) **15**:1753–1766.

[7] Babarit, A., Clément, A., Ruer, J. and Tartivel, C. SEAREV: a fully integrated wave energy converter. Proceedings of the offshore wind and other Marine Renewable Energies (OWEMES) (2006).

[8] McCabe, A.P., Aggidis, G.A. and Widden, M.B. Optimizing the shape of a surge-and-pitch wave energy collector using a genetic algorithm. Proceedings of the offshore wind and other Marine Renewable Energies (OWEMES) (2010) **35**: 2767-2775.

[9] Zhang, J., Li, C., He, H. and Zang,X. Optimization of a Multi-pendulum Wave Energy Converter. The Open Electrical & Electronic Engineering Journal (2015) **9**: 67-73.

[10] Morison, J.R., O'Brien, M.P., Johnson, J.W. and Schaaf, S.A. The forces exerted by surface waves on piles. Petroleum Transactions of AIME, (1950) **189**:149-157.

[11] Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. Numerical Recipes in FORTRAN 77. Cambridge University Press, (1992).

APRENDIX 1

ARCHIMEDES FORCE :

$$F_{ar1x} = \rho_e g L_1 R_1 y_1 \left(\cos\left(\theta_L + \frac{\eta_1}{R_1}\right) - \cos\left(\theta_L + \frac{\eta_2}{R_1}\right)\right) - \frac{\rho_e g L_1 {R_1}^2}{4}\begin{pmatrix} \cos\left(2\left(\theta_L + \frac{\eta_1}{R_1}\right)\right) \\ -\cos\left(2\left(\theta_L + \frac{\eta_2}{R_1}\right)\right)\end{pmatrix} \quad \text{(A1-1)}$$

$$F_{ar1y} = \frac{\rho_e g L_1 {R_1}^2}{2}\left(\frac{\eta_2 + \eta_1}{R_1} + 2\theta_L\right) + \rho_e g L_1 R_1 \left(\sin\left(\theta_L + \frac{\eta_1}{R_1}\right) + \sin\left(\theta_L + \frac{\eta_2}{R_1}\right)\right)\left(\frac{R_1}{4} - y_1\right) \quad \text{(A1-2)}$$

$$F_{ar2x} = \rho_e g L_2 R_2 (y_1 + Lsin(\alpha) - R_2 cos(\alpha_2))\left(cos\left(\theta_{L2} + \frac{\eta_3}{R_2}\right) - cos\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right) - \frac{\rho_e g L_2 {R_{21}}^2}{4}\left(cos\left(2\left(\theta_{L2} + \frac{\eta_3}{R_2}\right)\right) - cos\left(2\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right)\right) \quad \text{(A1-3)}$$

$$F_{ar2y} = \rho_e g L_2 R_2 \left(sin\left(\theta_{L2} + \frac{\eta_3}{R_2}\right) + sin\left(\theta_{L2} + \frac{\eta_4}{R_2}\right)\right)\left(\frac{R_2}{4} - y_1 - Lsin(\alpha) + R_2 cos(\alpha_2)\right) + \frac{\rho_e g L_2 {R_2}^2}{2}\left(\frac{\eta_4 + \eta_3}{R_2} + 2\theta_{L2}\right) \quad \text{(A1-4)}$$

With :

$\theta_L = arcos\left(\frac{y_1}{R_1}\right)$, $\theta_{L2} = arcos\left(\frac{y_1 + Lsin(\alpha) - R_2 cos(\alpha_2)}{R_2}\right)$,

$\eta_1 = A_m \sin(\omega t - k(x_1 - R_1 sin\theta_L))$,

$\eta_2 = A_m \sin(\omega t - k(x_1 + R_1 sin\theta_L))$,

$\eta_3 = A_m \sin(\omega t - k(x_2 - R_2 sin\theta_{L2}))$,

$\eta_4 = A_m \sin(\omega t - k(x_2 + R_2 sin\theta_{L2}))$,

A_m is the amplitude of the wave of pulsation ω and wave number k.

MORISON FORCE:

$$F_{mix} = \rho_e C_m V_i \ddot{x}_i + \frac{1}{2}\rho_e C_d S_i \dot{x}_i |\dot{x}_i| \quad \text{(A1-5)}$$

$$F_{miy} = \rho_e C_m V_i \ddot{y}_i + \frac{1}{2}\rho_e C_d S_i \dot{y}_i |\dot{y}_i|, \quad \text{(A1-6)}$$

Where $\dot{x}_i$ and $\ddot{x}_i$ are respectively the speed and the acceleration of the cylinder i along $\overrightarrow{Ox}$, $\dot{y}_i$ and $\ddot{y}_i$ are respectively the speed 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_i is the volume of the body.