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NUMERICAL SIMULATIONS FOR HYDRODYNAMIC TORQUE DETERMINATION IN CASE OF FIXED OSCILLATING WAVE ENERGY CONVERTERS

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Abstract: *Due to their low impact and high power flux, wave energy converters have unrivaled potential. Studies and research are needed, that will lead to the development of more efficient and low maintenance equipment. The paper presents the mathematical model for determining the total torque (hydrodynamic plus inertial) respectively the forces and speeds that can be transmitted to an electric generator, from a wave energy converter of Fixed oscillating wave surge, type. The mathematical model was transposed into Matlab Simulink and simulated in this environment, and the results obtained will be compared with experimental results in another paper.*

Keywords: *Renewable energy; wave energy; mathematical model.*

1. Introduction

With a power flux of 2…3 kW/m^2 resulting from the action of wind energy (0.4…0.6 kW/m^2) which in turn comes from solar energy (0.1…0.3 kW/m^2), the wave energy capture (WEC) systems, have become increasingly studied in the last period, being part of the renewable energy sources [1]. There are several categories of wave energy converters classified according to their operating principles, into: attenuators, point absorbers, oscillating wave surge converters (OWSC), oscillating water columns (OWC), terminators or submersed pressure differential devices, according to [2,3]. The principle sketches are shown in Figures 1 and 2.

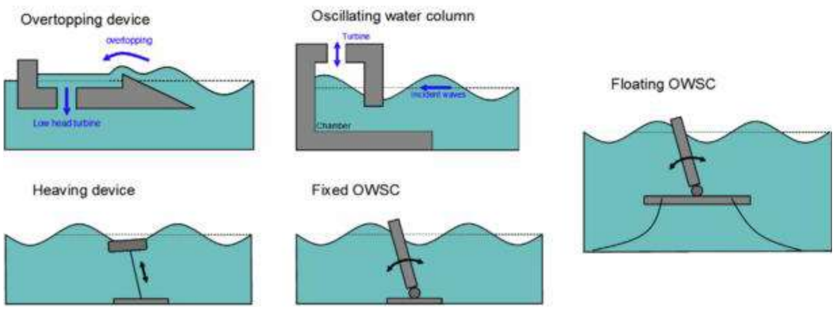


Fig. 1. Wave energy converters classification by [2]

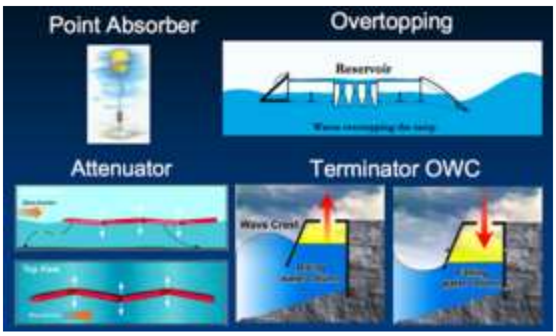


Fig. 2. Wave energy converters classification by [3]

In figure 3 is presented the Capture Width Ratio (CWR), $CWR = \frac{Absorbed\ power}{Incident\ power \cdot Device width}$, for the existing wave energy converters.

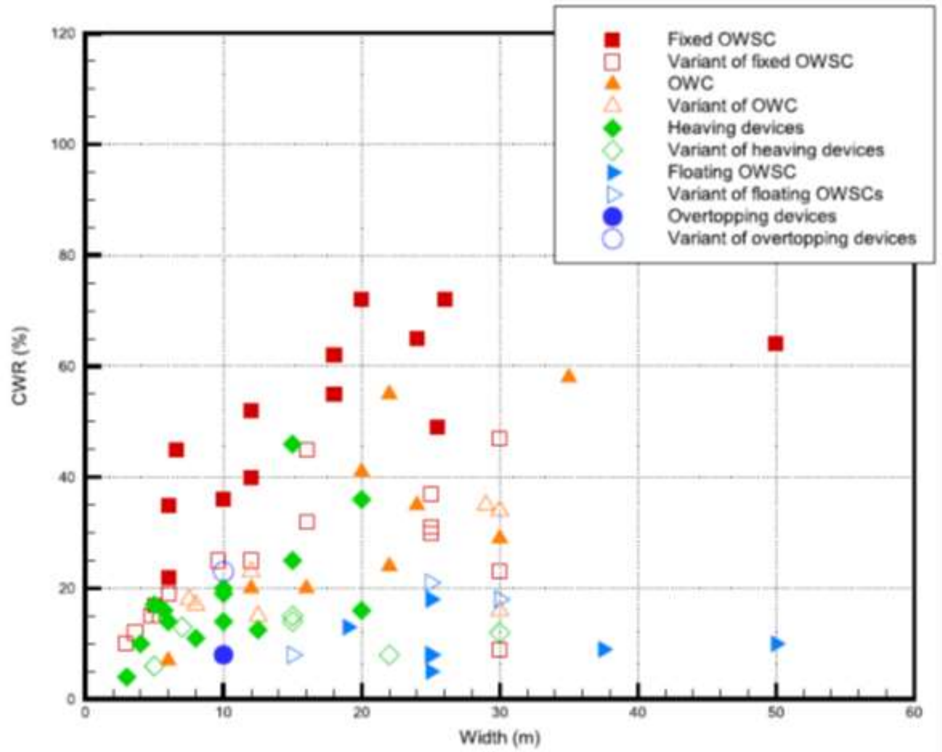


Fig. 3. Fraction of wave power flowing through the device that is absorbed versus Width of the WEC by [3]

However, wave energy technology is still in the research and development stage. Therefore, levelized energy cost for Wave Energy Converters designs is still high, compared to other renewable energy technologies, such as wind and solar [4].
To identify the devices of interest, eventually closest to commercial applicability, several are the aspects that need to be considered and to serve as basis to classify the existing devices, as several are the key aspects contributing to the technical and economic feasibility and success of a project. The main aspects are: the dynamics of the device and the principle according to which it interacts and extracts energy from waves (Power Take Off); the mooring and station keeping characteristics. Furthermore, aspects like building, installation and maintenance are also important for decision making. [5]
Because the Fixed OWSC systems have the highest CWR, the present paper refers to the development of a mathematical model for predicting the behavior of vertical flap structures in wave conditions, for this category of wave energy converters. Thus, being able to simulate, still at the concept level, the forces, respectively the power exerted by waves on the system. Power Take-Off (PTO) system, which can be: Hydraulic motor; Hydraulic turbine or Linear generator, is not the subject of the present work.
The theory of linear flow potential has proven to be successful in anticipating the behavior of devices under different practical conditions. This theory of potential linear flow can be used to describe fluid flow, by applying the conditions that exist at the boundary of the fluid domain. Thus, this theory is also applicable in the case of wave energy converter with vertical flap. When analyzing the waves, some assumptions are taken into account, namely that the fluid is incompressible and irrotational. Applying the law of mass conservation and Laplace's equation to the fluid imposes the incompressibility of the fluid. Due to the fact that the fluid is irrational, it allows simplifying the expression of the flow velocity as a gradient of a scalar potential, Φ, called velocity potential.

Another simplification is made by asserting that the radiated wave field can be described as the overlap of the waves created by each of the six degrees of freedom of an oscillating body.

2. Mathematical model

To design, analyze and optimize the wave energy converters, the mathematical model has an essential role, being able to develop and manipulate the configuration of the system at the virtual level with significantly lower costs compared to the physical prototype. The resulting virtual system can be analyzed and optimized, in this phase, until it meets the required criteria.
The sketch of the WEC studied in this paper, based on which the mathematical simulation model is developed for determining the forces, displacements and speeds, is shown in Figure 4.

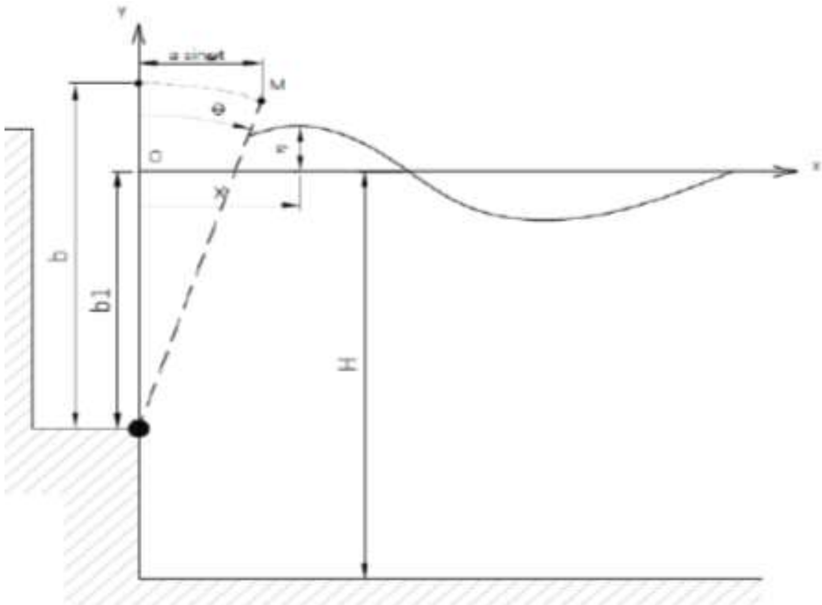


Fig. 4. 2D model for Vertical flap WEC

In order to determine the hydrodynamic moment, one starts from a function of potential of the water movement speed, Φ, which generates the movement of the flap, defined as follows:

$$\Phi = \frac{2a\omega}{b}\left\{\frac{\left(\frac{b_1\omega^2}{g}-1\right)\cosh k_0 H+\cosh k_0(H-b_1)}{k_0^3\left(H+\frac{g}{\omega^2}\sinh^2 k_0 H\right)}\sin(\omega t-k_0 x)\cosh k_0(y+H)-\right.$$
$$\left.-\cos\omega t\sum_{m=1}^{\infty}\frac{\left(\frac{b_1\omega^2}{g}-1\right)\cosh k_m H+\cosh k_m(H-b_1)}{k_m^3\left(H-\frac{g}{\omega^2}\sin^2 k_m H\right)}e^{-k_m x}\cos k_m(y+H)\right\} \tag{1}$$

where: H-water depth; b - height of the flap; b_1 - the distance from the pivot point of the flap to the free surface of the water; a - the amplitude of the movement of the highest point of the flap; θ - angular displacement of the flap; ω - angular velocity of the flap; η - water elevation; B - the width of the flap; g - gravitational acceleration; k_0 and k_m are the roots of equations (2), respectively (3):

$$k_0 \tanh k_0 H = \frac{\omega^2}{g} \tag{2}$$

$$-k_m \tan k_m H = \frac{\omega^2}{g} \tag{3}$$

The hydrodynamic force, F, is obtained by summing the forces given by the instantaneous pressure on each unit of area on the flap.
The hydrodynamic torque is obtained by multiplying by the force with distance.

$$M_H = \int_{-b_1}^{0} Bp(b_1 + y)dy \tag{4}$$

The value of the pressures is obtained from the relation:

$$p = \rho \left(\frac{\partial \Phi}{\partial t}\right)\Big|_{x=0} - \frac{q^2}{2}\rho - \Omega\rho \tag{5}$$

where: q - the velocity of the water particle; Ω=g·y - the gravitational potential.

Substituting (5) into (4), we obtain: $\frac{M_H}{B\rho} = \int_{-b_1}^{0} (b_1 + y) \left\{ \left(\frac{\partial \Phi}{\partial t}\right)\Big|_{x=0} - \frac{q^2_{x=0}}{2} - \Omega \right\} dy$ (6)

$$\left(\frac{\partial \Phi}{\partial t}\right)\Big|_{x=0} = \frac{2a\omega}{b}\{A \cosh k_0(y + H)\cos \omega t + \sin \omega t \sum_{m=1}^{\infty} B_m \cos k_m(y + H)\} \tag{7}$$

$$q^2_{x=0} = \left(\frac{\partial \Phi}{\partial x}\right)^2\Big|_{x=0} + \left(\frac{\partial \Phi}{\partial y}\right)^2\Big|_{x=0} \tag{8}$$

$$\left(\frac{\partial \Phi}{\partial x}\right)\Big|_{x=0} = \frac{2a\omega}{b}\{-Ak_0 \cosh k_0(y + H) + \sum_{m=1}^{\infty} k_m B_m \cos k_m(y + H) \cos \omega t\} \tag{9}$$

$$\left(\frac{\partial \Phi}{\partial y}\right)\Big|_{x=0} = \frac{2a\omega}{b}\{Ak_0 \sinh k_0(y + H) \sin \omega t + \sum_{m=1}^{\infty} k_m B_m \sin k_m(y + H)\cos \omega t\} \tag{10}$$

where,

$$A = \frac{\left(\frac{b_1\omega^2}{g} - 1\right)\cosh k_0 H + \cosh k_0(H - b_1)}{k_0^3\left(H + \frac{g}{\omega^2}\sinh^2 k_0 H\right)} \tag{11}$$

$$B_m = \frac{\left(\frac{b_1\omega^2}{g} - 1\right)\cosh k_m H + \cosh k_m(H - b_1)}{k_m^3\left(H - \frac{g}{\omega^2}\sin^2 k_m H\right)} \tag{12}$$

Substituting (9) and (10) into (8) we obtain:

$$q^2_{x=0} = \left(\frac{a\omega}{b}\right)^2 \left\{(b_1 + y)^2 \cos^2 \omega t + b_1^2 \operatorname{sech}^2 \frac{\omega^2 H}{g} \sinh^2 \frac{\omega^2(H+y)}{g} \sin^2 \omega t\right\} \tag{13}$$

Thus, the expression for the hydrodynamic moment is obtained by replacing relations (7) and (13) in relation (6):

$$M_H = B\rho\frac{a}{b}\omega^2\left\{2A\left[\frac{b_1}{k_0}\sinh k_0 H - \frac{1}{k_0^2}(\cosh k_0 H - \cosh k_0(H - b_1))\right]\cos \omega t + 2\left[\sum_{m=1}^{\infty} B_m\left[\frac{b_1}{k_m}\sin k_m H - \frac{1}{k_m^2}(\cosh k_m H - \cosh k_m(H - b_1))\right]\right]\sin \omega t - \frac{a}{8b}b_1^4\cos^2 \omega t + \frac{1}{6}\cdot\frac{gb_1^3}{\frac{a}{b}\omega^2} + \frac{a}{8b}b_1^2 \operatorname{sech}^2\frac{\omega^2 H}{g}\left[b_1^2 - \frac{gb_1}{\omega^2}\sinh\frac{2\omega^2 H}{g} + \frac{1}{2}\left(\frac{g}{\omega}\right)^2\left(\cosh\frac{2\omega^2 H}{g} - \cosh\frac{2\omega^2(H-b_1)}{g}\right)\right]\sin^2 \omega t\right\} \tag{14}$$

The moment of inertia is determined with the relation:

$$M_I = \frac{I}{g}\frac{\partial^2\theta}{\partial t^2} = \frac{I}{g}\frac{a}{b}\omega^2 \sin \omega t \quad (15)$$

where I - the mass moment of inertia.

3. Simulations results and Conclusions

For solving the equations numerically, it can be used Matlab / Simulink environment, with which it can easily model, simulate and optimize the mathematical system.
The input data for the type of wave energy converter studied in this paper (the dimensions are applicable to an experimental model):
a=1 m; b=3.892 m; b_1=2.897 m; B=0.7 m; ρ_{water}=1020 kg/m^3; b_y= 1,754 m; g=9,8 m/s^2; H=3.892 m; ω_{max}= 10 º/s = 0.17453 rad/s.

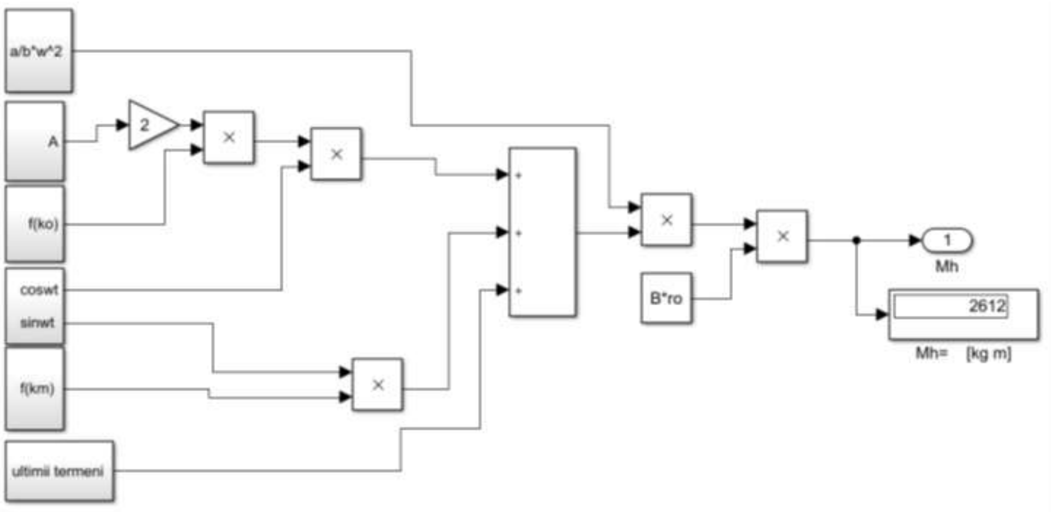
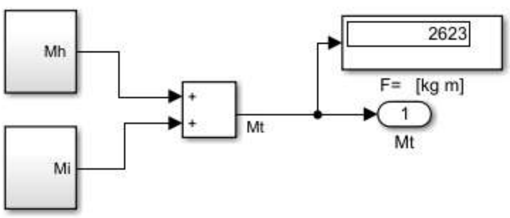


Fig. 4. Simulink model for Hydrodynamic moment (contains 6 subsystems)

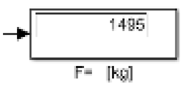
The total resistive moment consists of the hydrodynamic moment and the moment of inertia of the entire flap assembly, as follows:

$$M_T = M_H + M_I \quad (16)$$



For these types of energy capture systems, the energy transfer can be done with hydraulic cylinders, so it is necessary to know the total resistance force that can act on the cylinder. From the expression of the total resistant moment, determine the resistant force using the equilibrium relation of the forces at the point of pivot of the pallet as follows:

$$F \cdot b_y = M_T \quad (17)$$



where F, is the resistive force and b_y - the distance between the pivot point of the flap and the center of the rotating coupling between the cylinder rod and the flap).
Due to the high speed with which the expected results are obtained, in the case of numerical modeling and simulation, it is also proved with these applications that when developing new systems, the possibility of optimization offered by numerically simulated mathematical models makes them a very favorable technical-economic solution.
It is further proposed to study the possibilities of energy transmission from the Fixed OWSC, through pressurized liquids, to hydraulic turbines or motors. For these systems, besides energy efficiency, the control strategy is very important, which must be able to transmit all the energy captured from the waves to the electric generator.

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