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Development of a novel multi-level hybrid methodology for a new concept of Wave Energy Converter (WEC)

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Abstract

Successful WEC design and development needs massive experimental and in-field studies to cover different aspects of hydro-servo-elastic-geo interaction. Consequently, the lack of fairly accurate modeling methodology has inevitable effects on developing cost-effective harnessing technologies. Through this paper, a novel multi-level methodology combining experimental and numerical simulation is presented for a new WEC concept which significantly decreases the time-consuming process of concept validation. The methodology is comprised of multi-level numerical and experimental studies that are developed for reliable while the fast representation of a WEC device. The methodology can be easily tailored and adapted for different phases of analysis and design of any type of hybrid concept or single WEC devices. The proposed modelling methodology is hybrid multi-level experimental numerical simulations and is developed based on lessons learned and the expected challenges in representing a device. The proposed methodology has the advantage of easily being adapted for the fast-paced industry environment. The case study WEC device is also a new concept inspired by nature and in its first levels of concept validation. This concept is expected to operate efficiently even in areas with less energetic waves. The primary shape of the moving part of the device is inspired by nature to overcome resistance forces and increase the penetration and motion in water. The shape is also further improved considering manufacturing possibilities and the required symmetry for the device operation in the real sea. The corresponding numerical results are also presented along with a novel systematic modeling methodology to show the efficiency of the methodology in the development process of WEC.

Key words : WEC design and development, Numerical simulation, Experimental tests, Hydrodynamic optimization, Multi-level hybrid methodology

1. Introduction

There is a lot of untapped energy in waves that could contribute to the overall energy picture; however, wave energy converters are still at initial development phases [1] and the process to refine new technologies is ongoing. One of the important challenges in the way of commercialization is finding the optimum design for a specific device in a particular site e.g. [2]. Among different concepts introduced in recent years, wave-activated bodies are recognized with higher hydrodynamic power efficiency in comparison to other WEC types [3].

This paper deals with the development of a novel concept of WEC devices by using a new multi-level hybrid methodology. The WEC concept is inspired by nature to increase the penetration of the oscillatory part and decrease the resistant forces [4]. Drag and viscous effects could reduce the available power [5]; therefore, it is expected that by decreasing the drag effect, the power performance is enhanced. For the primary shape and dimension ratio of the oscillating body, the dimensions of taxidermy specimen swordfish are used. Swordfish is known as a specimen that is gone through several evolutionary processes to be drag efficient [6], further explanation regarding the concept development is provided in Section 2.

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A new methodology comprising multi-level theoretical, experimental, and numerical is proposed for WEC analyses and design (see Section 3). The concept of this methodology is to overcome the difficulty in simulating the whole hydro-servo-elastic-geo interaction of any kind of WEC device. In this methodology, the required level of sophistication will be used based on the engineering judgment, and whenever possible the most simple while fairly accurate models are used.

The wave-structure interaction is one of the important aspects of WEC device. Some parameters representing the interaction are difficult or impossible to be estimated by an analytical formula such as darg effects. It also applies to other sources of damping [7] such as mechanical damping. For this study, the results of the previous studies for hinge base WECs as non-dimensional mechanical damping are used [8]. The drag and the fluid flow around the body are also investigated by using multi-level Micro modeling.

The model is gradually developed with different levels of complexity to provide a thorough understanding of the fluid flow and the simplifications that can be applied without missing important effects. By reaching enough accuracy in 2D model, an optimization algorithm is combined with Navier- stokes equation to study and optimize the streamlined body. The most advanced model is used to prove that the drag can be negligible in the simulation. Since then, a Macro model is developed to consider the general behavior of the structure to incoming waves and with the presence of PTO. The Macro model for the fluid-structure interaction consists of the partial differential equation for simulating fluid and ordinary differential equation for the ideal dynamic representation of the WEC floating body. The optimized mass, center of rotation, and PTO coefficients are found by Macro modeling. The study will be continued based on the developed methodology for further development of the Sword WEC.

2. Concept development

The oscillating body of the WEC is inspired by one of the fastest animals in the sea, swordfish, with recognized drag efficiency adaptation during the evolutionary processes. Indeed, the goal was to develop an oscillatory shape with rapid penetration and drag resistancy. Studying the shape of the taxidermy specimen swordfish [10] and regenerating the shape for practical usage is shown in Fig. 1.

Fig. 1 Concept development

As previously mentioned the oscillatory part will be used for OWEC device application. The absorbing energy mechanism and how it could be installed on different types of support structures are shown in Fig. 2. The oscillatory body is supposed to be partially submerged and will slam into the free surface interface during the oscillations and rotation around the hinge. The oscillatory part and the rod can be mounted on various types of support structures appropriate for the candidate site. As can be expected for each candidate site, the required tuning of the shape and dynamic characteristics should be conducted. The focus is to develop a small size WEC due to its benefits for future series-manufactured plants and development costs [9].

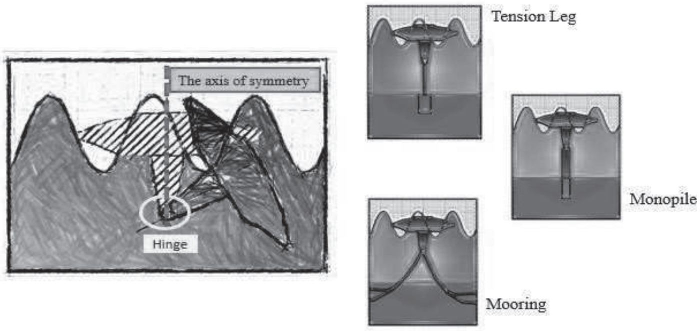


Fig. 2 Absorbing energy mechanism and support structures

3. Multi-level hybrid methodology

Multi-level Micro-and Macro-modelling composed of experimental and numerical simulation is used to respond to the need for a representation of the whole device for different phases of analyses and design. While Micro-modeling considers all possible details to accurately represent the physical phenomena, Macro model simulates a general representation and mainly uses the simplified governing equations. Consequently, the unknowns are decreased and the interpretation of the results can be conducted with less computational and time effort. Although it cannot precisely represent the local behaviour, it can be used for global analyses or in combination with Micro-modeling and experimental tests. Fig. *3* shows the flowchart of analyses and the correlation between Macro- and Micro- modelling for different phases from the primary assessment to various stages of analyses and design procedure.

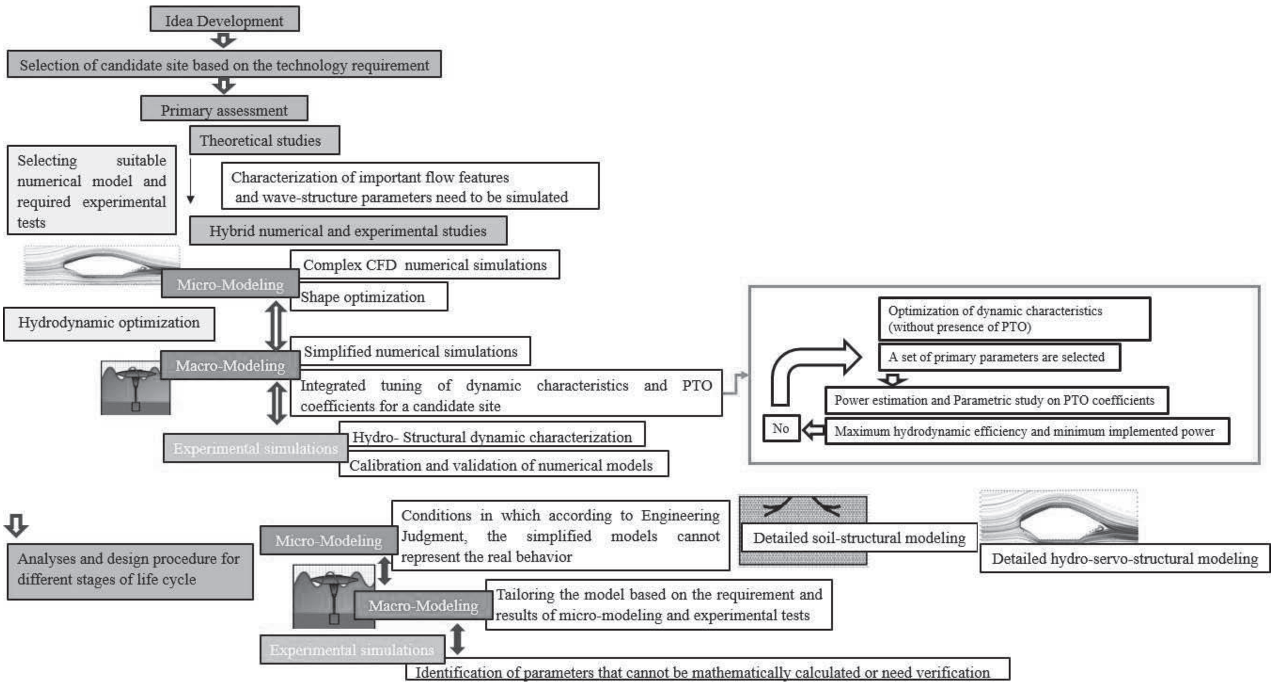


Fig. 3 Flowchart of hybrid theoretical, experimental, and numerical analyses

Here, the developed methodology is used for the first phases of the concept development and tuning the device characterization for the specific site of operation. However, as previously mentioned, the proposed methodology can be used for various stages of analyses and design. For example, it would be possible to use mathematical models to represent some behaviors that are difficult to be captured by mapping sensors. Thus, instead of a complicated numerical model or fully sensored experimental tests, a more simplified while informative Macro model can be used. This model not only can receive data from the experimental tests but can also be used in connection with various kinds of tests such as accelerated testing of the components. Stated differently as is also shown in Fig. 3, the Macro model and experimental tests have a bidirectional connection.

3.1 Theoretical study

Theoretical studies can significantly help to make a clear picture of the required tests and numerical simulations needed to be conducted for a better understanding of the device's behavior. The primary idea was to study the application of this WEC for the Iranian sea and to be more accurate for the south of the Caspian Sea, near Ramsar [10] which is reported as one of the highest energy resources[11]. For the feasibility study and tuning of the WEC for the site, an average 15 years wave period of 4.40 s and a height of 0.51 m as reported in [11] has been chosen. For calculating fluids' dynamic viscosity, an average annual air temperature (20^{O} C) above the Caspian Sea in Iranian borders [12,13] has been considered. Consequently, the corresponding fluid’s dynamic viscosity can be assumed $10^{-3}\,Ns/m^{2}$ [14]. The velocity of the wave for this site is not going beyond 2.5 m/s. The Reynolds number is calculated for the proposed shape and it will be around 2×10^{5} for the maximum velocity equal to $2.5\ m/s$. Reynolds number provides a better understanding of fluid behavior. This number suggests that the flow around the device would enter the turbulent behavior which means shaping bubbles, growing in size, and finally bursting[15]. However, it should also be considered that the calculated Reynolds came from an equation of $\rho vl/\mu$; ρ is the fluid density; v is the velocity; l is the characteristic length (in this case, the distance from the leading edge); and μ is the fluid’s dynamic viscosity. As can be seen in this equation, only the characteristic length of the shape is coming into account. Therefore, the prediction for fluid flow can be useful but needs further studies and examination.

A	a	T	L0	L	K	c	$2\pi\frac{A}{a}$	$\frac{A}{a}$	Ka	$\frac{d}{L}$	$\frac{H}{L}$	$\left.\frac{H}{L}\right)_{max}$
0,26	0,80	4,40	30,23	25,25	0,25	5,74	2,00	0,32	0,20	0.20	0,02	0,01

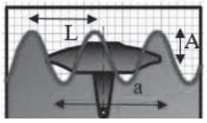


Fig. 4 Wave-body interaction parameters

Fig. *4* summarizes the wave-body interaction parameters calculated from the theoretical formula. Ka show the scattered waves and spreading of the energy in other directions of the incoming wave by the presence of the body [16]. As it can be seen this parameter is less than one. As parameter d/L suggested the shallow water condition is governed the wave propagation which means that the wave characteristics are related to the depth [17]. As the device operation is considered nearshore, the possibility of wave breaking and dissipating of energy should also be considered [18].

As is shown in Fig. *4*, the ratio of wave height to wavelength passes the maximum ratio suggested by Miche equation [17]. On the other hand, this ratio is still less than the criteria by Longuet-Higgins and Fenton, one of the accurate values for breaking wave index [18].

The theoretical studies provide us with a better understanding of the wave-structure interaction. According to this preliminary study, a sophisticated model of wave-body interaction seems necessary to provide a deeper knowledge of flow regimes and the spreading of energy around. From the theoretical studies, it would be possible to anticipate the required level of sophistication for the simulation. The first level of numerical analyses will represent the Micro-modeling of fluid around flow and is used for shape optimization.

3.2 Numerical analyses- Micromodeling

The part related to wave-structure interaction is an essential part in defining the WEC behavior and needs to be investigated thoroughly. Due to the uncertainties involved in the wave-structure interaction, several experimental and numerical simulations need to be conducted to verify the hypothesis. CFD simulation can play an important role and provide a picture of the fluid flow passing the device. For this part of the analysis, Navier- stokes equations for describing the fluid flows by the conservation of mass, momentum, and energy are used [18–20]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\ .\nabla)\boldsymbol{u} = \nabla.[-p\mathbf{I} + \tau] + \mathbf{F} \tag{2}$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + (\boldsymbol{u}\ .\nabla)T\right) = -(\nabla.q) + \quad \tau{:}\,\boldsymbol{S} - \frac{T}{\rho}\frac{\partial \rho}{\partial T}\bigg|_n \left(\frac{\partial p}{\partial t} + \left((\boldsymbol{u}\ .\nabla)p\right)\right) + \boldsymbol{Q} \quad (3)$$

In these equations, ρ is the density $[kg/\mathrm{m}^3]$; u is the velocity vector $[\mathrm{m}/s]$; p is pressure $[Pa]$; τ is the viscous stress tensor $[Pa]$; F is the volume force vector $[N/m^3]$; Cp is the specific heat capacity at constant pressure $[J/kg.\ K]$; T is the absolute temperature $[K]$; q is the heat flux vector $[W/m^2]$; Q contains the heat sources $[W/m^3]$; S is the strain-rate tensor:

$$\boldsymbol{S} = \frac{1}{2}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) \quad (4)$$

For practical engineering usage, these equations can be further simplified as the Reynolds-averaged Navier-Stokes (RANS) equation:

$$\rho\frac{\partial \boldsymbol{U}}{\partial t} + \rho\boldsymbol{U}.\nabla\boldsymbol{U} + \nabla.\ \ \overline{(\rho u'\otimes u')} = -\nabla P + \nabla.\mu(\nabla\boldsymbol{U} + (\nabla\boldsymbol{U})^T) + \mathbf{F} \quad (5)$$

Then two-equation models of $k - \varepsilon$ (Turbulent kinetic energy k- Turbulent dissipation rate ε) for the calculation of the drag forces are used [21,22]. By using the Multi-level modeling, analyses are started from 2D simulation and are further progressed to 3D. Multi-level modeling provides the opportunity to step by step increase the complexity of the problem and figure out which parameters are important to be studied in detail. Moreover, in the process of developing a numerical model that is very sensitive to various factors such as time-stepping algorithm, mesh, and the solver selection; the 2D can help to find out the optimized setup of the model to tackle a 3D representation. Besides, for this specific WEC that its expected rotation is aligned with the wave direction, 2D model can be effectively used for the shape optimization in wave direction.

Consequently, a hybrid optimization algorithm and CFD solver are used for the shape optimization of the oscillatory part of the WEC. Fig. *5* shows the general dimensions and the points selected for the shape optimization. Flow around the shape and drag forces calculated for each generated shape are also shown in this figure.

Since it is not clear if the tail of the sword can also help for the drag adapting of the shape, the effect of the tail and its length are also studied. However, these studies show that the shape without a tail can provide a more streamlined body [23]. Formation of bubbles and hollow voids around the tail (could be observed in Fig. *5*) b.) suggests the presence of resistance forces against the device movement.

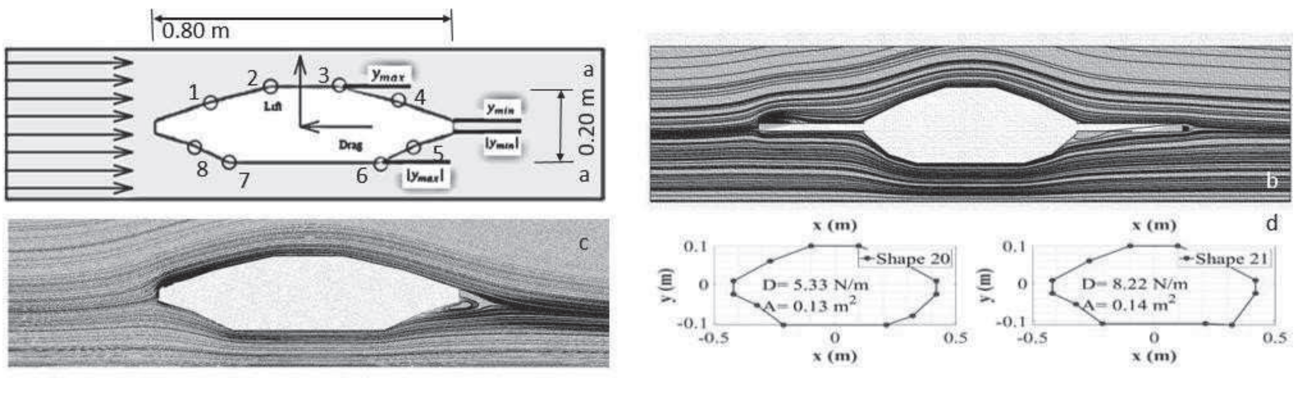


Fig. 5 2D hybrid optimization and CFD simulation; a) general dimension and selected points for the optimization; b and c) fluid flow around the generated shapes from the optimization; d) Exemplary calculated drag forces for generated shapes

Finding a better understanding of the fluid flow around the shape in 2D, leads to a better set-up for 3D simulation which confirms the findings of 2D. The generated optimized shape can provide a smooth transition of flow around it. By finding the optimized shape, it would be possible to go further in the operation of the device and its power performance. The next level is using the Macro-modeling for the calculation of power and its dynamic behavior.

It can be said that only experimental simulation could be used for determining the drag forces on an object [24], however by using a more accurate numerical model, it is possible to virtually simulate the wave-body interaction. By developing an optimized and streamlined body it can be safely assumed that the drag force can be neglected and eliminated from the Macro model.

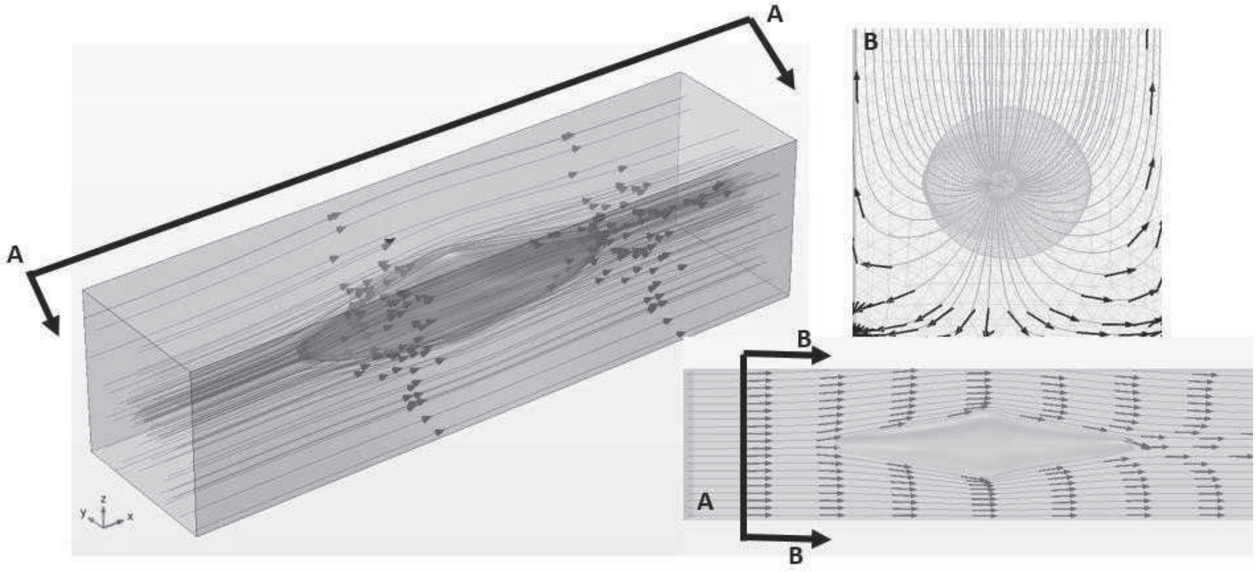


Fig. 6. Fluid flow around the generated shape from the optimization;

3.3 Numerical analyses- Macro modeling

The goal of this part is to find an accurate while fast representation of the device to estimate its power performance and it mainly deals with the tuning of the device's dynamic characteristics and PTO coefficients. For this reason, a dynamic model of WEC is coupled with potential theory representing the fluid flow around the device. Therefore, the fluid-structure interaction is simplified from the Navier-stokes but still is time-dependent and can catch the change that happens in each time-step in fluid and the corresponding rotation of the device. As previously mentioned the model is also simplified in terms of darg forces; as was found that the shape of the body provides a smooth transition of flow by the Micro modeling.

The pitch motion of the oscillatory part can be modeled by one degree of freedom:

$$I\ddot{\theta} + K_H\theta + K_P\theta + C_P\dot{\theta} + C_F\dot{\theta} = -\rho \int_s \varphi_t(z - h_r)\, ds \tag{6}$$

This equation mainly combines the ordinary differential equation (the dynamic representation of the device) with the solution of the partial differential equation representing the fluid flow. A numerical model with a fluid domain simulating the part of the selected site is combined with the dynamic equation. Further information regarding the development of this equation can be found in [8,25–28].

$I\ddot{\theta}$ and $K_H\theta$ are used to simulate the inertia and hydrostatic moments, the constants of I and K_H are analytically calculated [25]. K_P and C_P are representing PTO stiffness and damping paramters. The remaining part to complete the dynamic equation of the device is the damping term. Damping is difficult to be analytichly represented, and shuld be experimentally estimated. Here, since the device is rotating around a hinge, it can be safely assumed that the main loss of energy would be mechanical damping which is symbolized by C_F in Eq. 6. The nondimensional damping coefficient from the previous experimental tests on hinge-connected WEC is used for this model [8,10,27,28].

As was previously explained, the operation site is considered in the south of the Caspian Sea, near Ramsar. Therefore, the dynamic characteristics of the device are tuned for an average 15 years wave period of 4.40 s and a height of 0.51 m. For tuning the dynamic characteristics of the device the scale, mass, and the centre of rotation and their effects on the moment of inertia and hydrostatic stiffness and consequently on the natural period of the device are studied. Like any other part of the analysis and design procedure, tuning is an iterative process. It should be noted that tunning is the iterative procedure, and due to the interaction of different parts, all parameters should be in balance to make a device act as was anticipated for the maximum harnessing of the wave energy.

Four different masses (Mass 1 to Mass 4) corresponding with densities equal to 200, 300, 400, 500 $kg/m^3$and coordinate of the centre of rotation as a coefficient of the device height (H_D) are used for the simulation. For each mass, different locations for the hinge connection (centre of rotation) are considered. For each set, inertia and hydrostatic coefficients are calculated; an exemplary graph showing the change in these coefficients for Mass 1 is presented in Fig. *7*. Evidently, with the increment of centre of rotation, both inertia and hydrostatic stiffness are growing. Although the dimensions of these coefficients are different, they are presented in the same graph, to emphasize the growth rate of each with the place of centre of rotation.

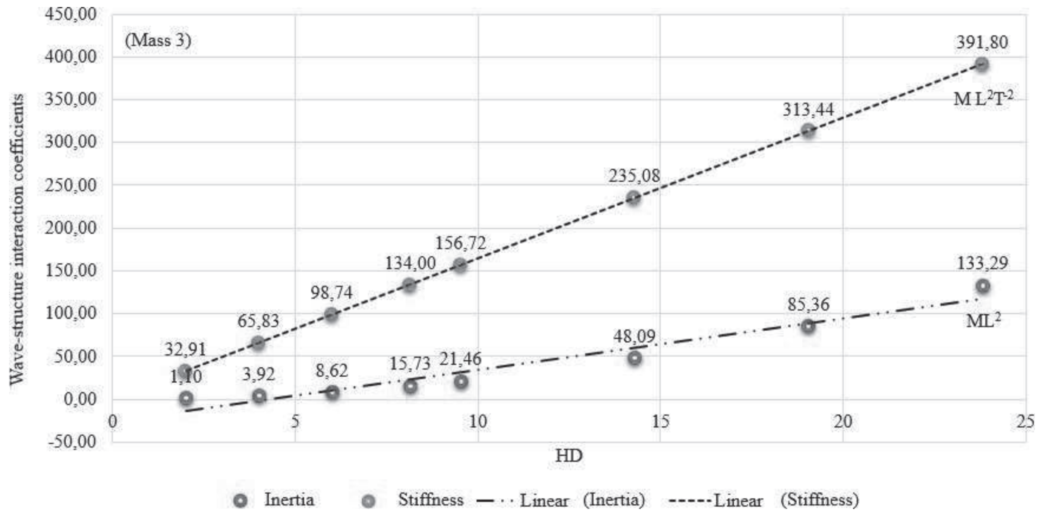


Fig. 7 Inertia and hydrostatic coefficients

The natural period (T) is calculated for each mass and centre of rotation. The classic formula $T = 2\pi\sqrt{m/k}$ [29] is used which can be re-symbolized for the current study as $2\pi\sqrt{I/K_H}$. Apart from the analytical estimation of the inertia and hydrostatic stiffness, and consequently the natural period; numerical simulations have also been conducted for each set of mass and centre of rotation to understand the effect of these parameters on the amplitude of rotation.

Studying time-series responses of a dynamic device like this WEC and concluding about the behavior is not a straightforward procedure. As can be seen, by changing the centre of rotation and mass, the dynamic characteristics are altered. Although, these changes can be in direction of making resonance in the system; increasing the stiffness is not always in our favor and can limit the device motion. Therefore, the results should be studied in terms of not only the period of the structure but also the amplitude of the response to the incoming waves.

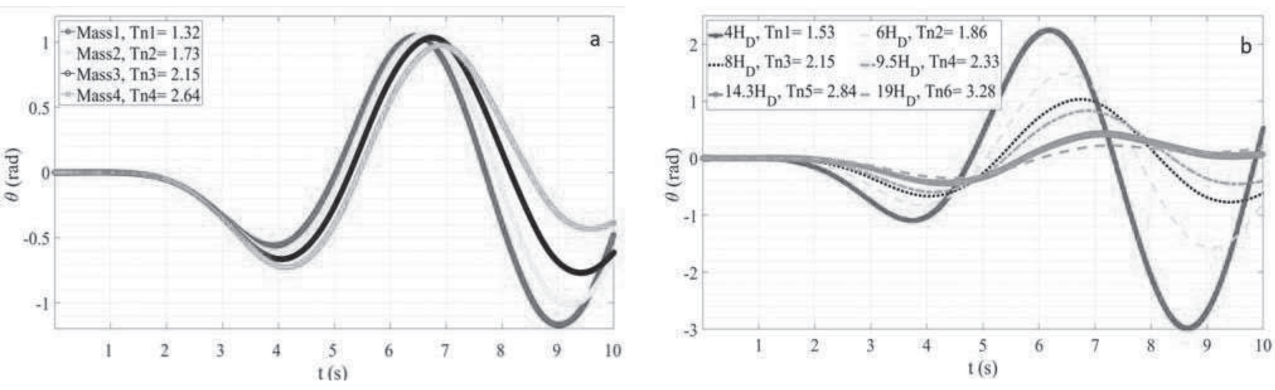
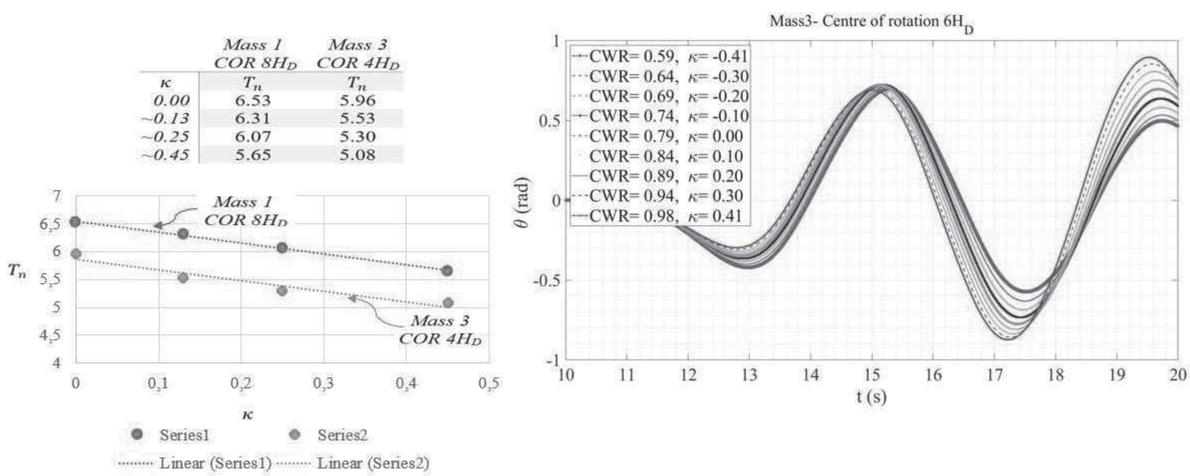


Fig. 8 Micro-modleing numerical results: a) Constant depth for different mass; b) Constant mass with various depth

Form the first set of tuning, the primary scale, mass, and centre of rotation are determined. The next step is optimizing the hydrodynamic performance by adding the PTO model to the system. It should be emphasized that the presence of PTO could also change the dynamic characteristics and consequently the response and power. Although the presence of damping would increase the natural period; the stiffness decreases it. Both stiffness and damping could restrain the amplitude. Therefore the hydrodynamic optimization is an iterative procedure that should include the effective parameters (see Fig. *3*).

For the optimization of PTO coefficients, some parameter bounds should be defined. First of all, it is expected that the device oscillates as an underdamped system [30]; therefore, the maximum implied damping should not extend the critical damping [10,27].Two parameters of $\xi = C_P/C_{cr}$ and $\kappa = K_P/K_H$ are introduced which connect the PTO damping and stiffness to the critical damping and hydrostatic stiffness, respectively. It is generally accepted that by increasing the complexity of a problem, the interpretation of the results become difficult. Therefore, for each parameter, a separate parametric study have been conducted. Fig. *9* shows the variation of natural period of the device due to the change in the Mass, centre of rotation, and PTO stiffness.

CWR presented in this graph is the ratio of the absorbed power (watt) to the available power (watt/m) multiplied by the active width (m), $CWR = P_{abs}/(width_{active} * P_w)$ [31,32]. As can be seen, tunning a WEC device should be done from a multistate point of view. As was explained Mass and COR can significantly change the dynamic characteristics which in turn could change the natural period of the device and the amplitude of rotation. On the other hand, the implied energy to the system by PTO can also alter dynamic characteristics. In different control schemes, by changing the implied PTO force, which here is simulated by damping and stiffness terms, the device is set to respond in resonance. On the contrary, these parameters can reduce the amplitude of oscillation. Therefore, it is essential to consider the effects of various parameters separately and then study their effects in the big picture. This method helps to exactly figure out and study the trend of a device's behavior under the change of one parameter.



	Mass 1 COR $8H_D$	Mass 3 COR $4H_D$
κ	T_n	T_n
0.00	6.53	5.96
~0.13	6.31	5.53
~0.25	6.07	5.30
~0.45	5.65	5.08

Fig. 9 Parametric study of PTO stiffness, mass, and center of rotation.

From these analyses, a primary set of Mass, COR, PTO stiffness, and damping were found, and then another set of analyses for optimizing the PTO coefficients have been conducted. The goal is to decrease the implemented energy and increase the hydrodynamic efficiency; accordingly, the design goal is to tune the device that it needs minimum stiffness to apply and produce the maximum power. The findings confirm that for the selected site, the combination of Mass 3 and COR around $2H_D$ can tune the device to make resonance with the average wave characteristics and the tunned system does not need any implemented energy in terms of PTO stiffness. While for the non-tunned system in terms of mass and centre of rotation, 40 % of hydrostatic stiffness should be applied to reach almost the same CWR. These findings show the importance of tuning the dynamic characteristics of a device for a specific site of operation.

4. Conclusion

The hydro-servo-elastic-geo interaction of any kind of WEC device made the simulation complicated and time-consuming, which in turn makes the engineering judgment and providing a reasonable solution to improve the behavior difficult and with lots of uncertainty.

Through this paper, a novel methodology comprised of theoretical, experimental, and numerical studies for the analyses and design of WECs is proposed. The methodology is further described by implying it to a novel WEC device in its early stage of development. However, the methodology itself can be used for any stage of analysis and design. The goal of this method is to speed up the process of understanding the device behavior with multi-level modeling techniques.

It allows to be tailored based on the information required to be obtained. The results confirm that the methodology is successful in improving the drag resistancy of the device with advanced Micro modeling and improving its hydrodynamic efficiency with Macro-modeling. It was shown that the tuned system doesn't need to imply the PTO stiffness, while untuned system needs almost 40% of the hydrostatic stiffness to reach the same efficiency. The proposed methodology will be used for the future development of this WEC with the combination of more advanced experimental tests.

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