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Simulation of a resonance-amplified floater oscillation in an open-type circular caisson

Yan-Xiang Lin, Da-Wei Chen, and Jiahn-Horng Chen

Abstract— **A new wave-energy harvesting system, consisting of an open circular caisson (or arc-shape caisson) and a PTO system connected to a floater inside the caisson, is studied in this paper. The caisson serves to amplify the incident waves locally through the harbour-resonance effect such that the heave motion of the floater is greater in both amplitude and speed; hence, more energy can be harvested.**

In the present study, the arc caisson is of 300 degrees (or the opening of the caisson is 60 degrees). The PTO is modelled as a constant damping force applied to the floater. The free open source CFD software OpenFOAM was employed for the investigation. The optimum wave amplification without the presence of floater and PTO was first addressed and the corresponding wave period determined. Then the effect of PTO damping and the motion of the floater were studied at the "best" incident wave found previously. The interaction of floater motion and wave was computed.

Keywords—**Wave energy, caisson, wave amplification, harbour resonance, wave energy converter.**

I. Introduction

WAVE energy is one of many forms of ocean energy. It attracts global attention because of its abundant resources and availability almost everywhere in the ocean. However, to harness wave energy, we still need to face many challenges arising from hostile ocean environments. Although many types of wave energy converters (WECs) have been proposed, the way to commercialization is still far ahead [1].

In addition to the technological issues involved in the WEC development, deployment, and operations, there are other dilemmas which need be circumvented if the wave energy in low latitudes, such as Asian areas, is going to be harnessed. Here, the wave energy density is only medium, compared to that in the prevailing westerlies. From the economic point of view, there are always debates whether it is worthwhile to harness ocean waves in the regions with medium or low energy density. To reduce the cost, Mustapa *et al*. [2] suggested that the device should be incorporated with other existing structures, such as breakwater. From the technical point of view, the devices developed for high wave energy density are not applicable in these regions, as pointed out by Liu *et al*. [3]. Furthermore, in low latitudes, there are tropical cyclones or severe cyclonic storms such as hurricanes and typhoons. They induce strong rotating winds and huge waves with very high energy density for only few days in a year. WECs designed for normal wave conditions in these regions are expectably vulnerable to their impact. There have been several reports in Asian region that the WECs were destroyed in a moderate typhoon (the wind speed ranging between 32.7 and 50.9 m/sec) or even a mild one (the wind speed ranging between 17.2 and 32.6 m/sec) when they were tested in the real sea.

Therefore, to harness the wave energy effectively and safely in low-latitude regions, we have to devise innovative strategies in the WEC design. Most approaches available in the literature are to improve the WEC efficiency in one way or another. Liang *et al*. [4] introduced a new type of power takeoff (PTO) system, the mechanical motion rectifier, and incorporate with a point-absorber WEC. They show that this type of PTO system can extract more power than that of a linear PTO system in regular waves. Sheng *et al*. [5]-[6] investigated and developed PTO control strategies to improve wave energy conversion. They proposed a new latching technology which can be implemented with the information of wave period only. They developed the strategies for both regular and irregular waves.

In addition to the PTO system, the effects of WEC types on the efficiency of wave energy conversion are also investigated. As an example, Alamian *et al*. [7] evaluated the existing WEC systems for the use in the Caspian Sea and concluded that the point-absorber WECs could be the best type to harvest wave energy there. However, each type of WECs has its own advantages and disadvantages. The conclusions from such investigations cannot be universal. More studies have been devoted to improving

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some particular type of WECs. For a few examples, Boccotti [8] and Boccotti *et al*. [9] introduced the new concept U-OWC, an OWC with an additional vertical duct. Boccotti [10] showed that its performance was better than the conventional one. The backward bent duct buoy (BBDB) is another significant way to improve WEC efficiency. It is a kind of floating OWC proposed by Masuda *et al*. [11] and has been proved that its primary conversion performance is better than other floating type devices [12]. The recent experimental study by Diaz *et al*. [13] also shows that BBDB OWC can be deployed in various sea conditions.

In addition to the OWC type of WECs, the efficiency study of oscillating wave surge converter (OWSC) is another example. Gomes et al. [14] investigated the dynamics and power extraction of bottom-hinged plate WECs. Their study shows that the best ratio of the capture width to the plate width for energy harvesting is 0.8 for regular waves and 0.65 for irregular waves. Chow *et al*. [15] examined by both numerical and experimental approaches the inertial effect on the performance of a bottom-hinged OWSC. They defined a parameter which is the square of sum of three mechanical-impedance terms associated with inertial effect and found that its minimum value maximized power capturing performance.

All kinds of efficiency improvement strategies are usually equally applicable and beneficial to WECs deployed in regions of both high and low energy densities. However, efficiency improvement is not able to circumvent the dilemma of medium/low potential wave energy density. This is evident because all efficiency improvement technologies which have been developed up to now are not able to remedy sufficiently the disadvantage of low energy density.

In the present study, we proposed the combination of an open caisson and a point-absorber type of WEC. The open caisson serves to amplify the wave energy locally inside it, provides protection to the WEC from the extreme waves due to typhoons, and restricts the WEC motion to a simple one which is mainly heaving. Therefore, the disadvantageous issues commonly faced in Asian region can be effectively gotten rid of. The present type of device is not derived from OWC and its theoretical background is also different from that of OWC. It is a new type of its own kind.

II. THE STUDY OF WAVE AMPLIFICATION INSIDE A CAISSON

Before examining the energy harvesting of the device which consists of an open caisson, a floater on the water surface inside the caisson and a PTO system connected to the floater, we first address the local wave amplification inside the caisson without the floater and PTO system. Two different types of caissons were examined in our study. The first type is a simple one, shown in Fig. 1(a). It has an opening of angle θ. The radius is r_1. The second type is shown in Fig. 1(b). It has two additional wave guides mounted on the caisson. The two wave guides are identical in size and form. It is a part of circular arc with radius r_2. In our study, we specified $r_1 = 2r_2$. This is arbitrarily specified without any particular intention of optimization.

A. Theoretical and numerical aspects

A wave of period T and height H propagates toward the caisson at an incident angle of $\alpha = 0°$. Due to the wave incidence, the water inside the caisson oscillates with a wave height S. Our computation shows that the wave height varies pointwise inside the caisson. We define the wave amplification factor R as the ratio of the wave height S inside the caisson to the incident wave height H. To compute the value of R, we specified S as the average of wave heights at five points: innermost, center, leftmost, rightmost, and entrance points.

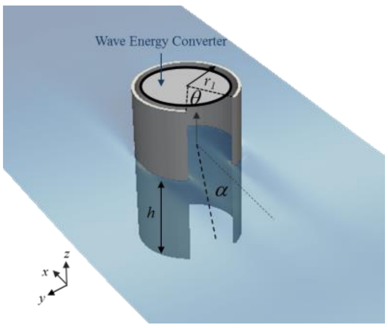
For the present physical problem, the hydrodynamic behaviours outside and inside the caisson are governed by the continuity and momentum equations

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

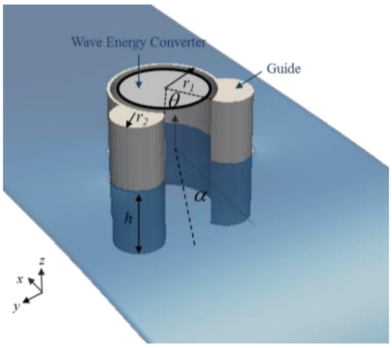
$$\rho\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = -\nabla p + \mu\nabla^2\mathbf{u} \tag{2}$$

where $\mathbf{u}$ is the velocity, ρ the water density, p the pressure, and μ the dynamic viscosity of the water, and t the time. Viscous effects can be important on the boundary of caisson and, therefore, are taken into consideration here.

To account for the turbulent effects, we decompose the velocity and pressure fields into the time-averaged and fluctuating quantities. Then the Reynolds-averaged Navier-Stokes equations are obtained through the time-averaging operation on Eqs. (1) and (2).

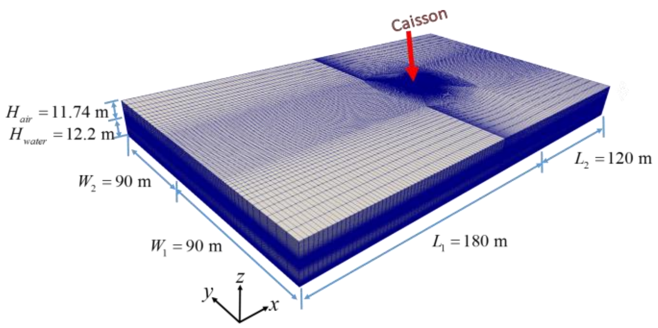


(a) Caisson without wave guides.

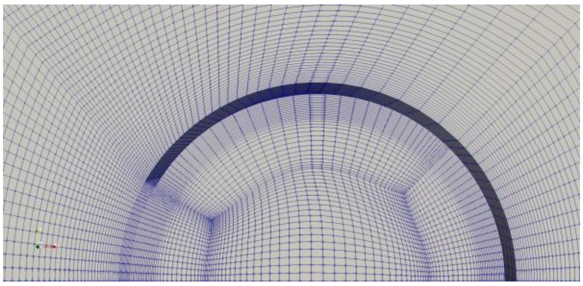


(b) Caisson with wave guides.

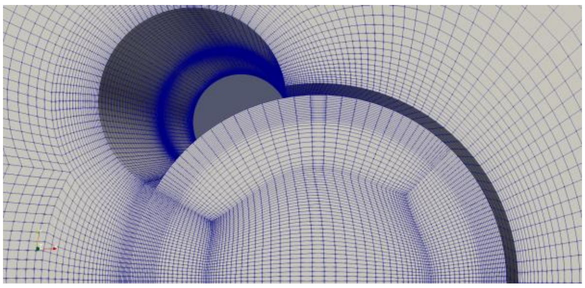
Fig. 1. Two types of caisson in an infinite water domain of finite depth.



(a) Computational domain.



(b) Mesh near the caisson without wave guides (top view).



(c) Mesh near the caisson with wave guides (top view).

Fig. 2. Truncated domain for computational purpose.

$$\nabla \cdot \bar{\mathbf{u}} = 0 \tag{3}$$

$$\rho\left[\frac{\partial \bar{\mathbf{u}}}{\partial t} + (\bar{\mathbf{u}} \cdot \nabla)\bar{\mathbf{u}}\right] = -\nabla \bar{p} + \mu \nabla^2 \bar{\mathbf{u}} + \nabla \cdot \boldsymbol{\lambda} \tag{4}$$

where the terms with overbar represent time-averaged quantities and $\boldsymbol{\lambda}$ is the Reynolds stress tensor due to the fluctuating physical terms. Here we adopt the standard k-ε model for turbulent effects.

In the present study, we set h = 12.2 m, r_1 = 9.14 m, r_2 = 4.57 m, H = 2.43 m, and θ = 60°. The thickness of the caisson wall is 0.64m. The incident wave period varies within the range of interest from 9 to 25 s.

The open source code OpenFOAM was adopted for this computational study. The OLAFOAM model based on OpenFOAM with the finite volume method approach was employed. OLAFOAM is a set of solvers and boundary conditions to generate and absorb water waves actively at the boundaries and to simulate their interaction with coastal structures [16]. The SIMPLE algorithm was used for the iterations of the velocity and pressure fields and the PISO algorithm for the time marching. In addition, in the solver, the volume of fluid method was used for the treatment of the free surface.

The infinite physical domain was truncated to form a finite region for computational purposes. After a series of careful examination of computed data, we decided the truncated region as follows. Shown in Fig. 2(a), the length, width, and depth of the domain are $L = L_1 + L_2$ = 180 m + 120 m = 300 m, $W = W_1 + W_2$ = 90 m + 90 m = 180 m, and $H_t = H_{air} + H_{water}$ = 11.74 m + 11.2 m = 22.94 m, respectively. Also shown in Fig. 1(a) is the mesh. The structured grid was designed and employed in the present study. The total numbers of grid points are about 1.29M and 1.54M for the caisson without and with wave guides, respectively. Figs. 2(b) and (c) show the mesh near both caissons from the top view. The wave guides make the structured mesh generation more difficult. However, we have taken care of these parts carefully without distorting the mesh.

B. Wave amplification inside the caisson

Fig. 3 shows the results of our computations. The waves are amplified at all wave periods selected for computations. While some amplification factors are close to unity, others are obviously much larger than unity. The effect on wave amplification for the caisson without the wave guides is evidently less than that with the wave guides. The computed velocity fields show that the flow speed distribution at the entrance of caisson with a pair of wave guides is much bigger than that without the wave guides. This results in a higher surface elevation at crest and lower surface elevation at trough in the caisson with the wave guides. This is to say that the wave height in the caisson with the wave guides is larger than that without the wave guides.

Furthermore, the peak amplification factors appear at T = 13 s for both caissons. Its value for caisson without the wave guides is about 2.02 and that with the wave guides is about 2.91. Since the wave energy density is proportional to the square of the wave amplitude, the present results indicate that the wave energy density inside the caissons is about 4.0 and 8.5 times, respectively, as much as that in the open waters. We can say that the harbour resonance can create significant effect on wave energy amplification.

In addition, the in the interval between T = 11 s and 15 s, the variation of the amplification factor is rather mild for both caissons. This is an additional advantage for wave energy harvesting purpose because it implies that the wave amplification is not sensitive to the wave period.

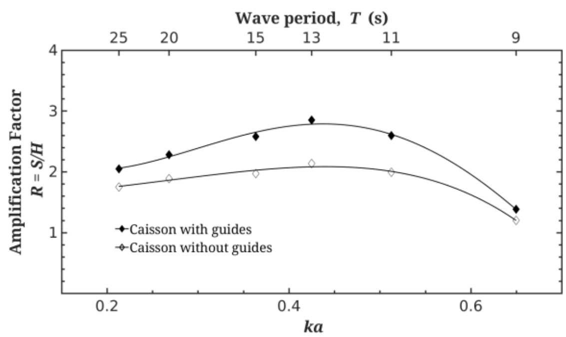


Fig. 3. Amplification factors for the caisson without and with wave guides (k: wave number; a: diameter of the caisson).

III. Power Take-Off with Constant Damping

The results shown in the last section clearly indicate that the caisson with a pair of wave guides results in better wave amplification. Therefore, we should focus on the system with the wave guides only. However, due to its complexity in geometry, we first conduct our computations for the caisson without wave guides for simplicity in the following.

C. *The system*

Now we add the WEC inside the caisson for the power take-off computations. The WEC consists of a floater and a PTO system. The whole system for analysis is shown in Fig. 4. The floater and the PTO system are connected to each other through some kind of mechanical device. For simplicity, the effect of PTO system which transforms wave energy to electricity is simulated by a constant damping with the coefficient of 10^6 kg/s. The damping force acts at the center point of the floater in the opposite direction of its motion as it moves up and down with the wave inside the caisson with wave guides. The floater is a cylinder with 8 m in diameter and 1 m in height. Its density is only half of that of water. It half submerges in water when it is calm. The shape of the floater is arbitrarily chosen for easy grid generation. The design of an optimal shape is not within the scope of the present study.

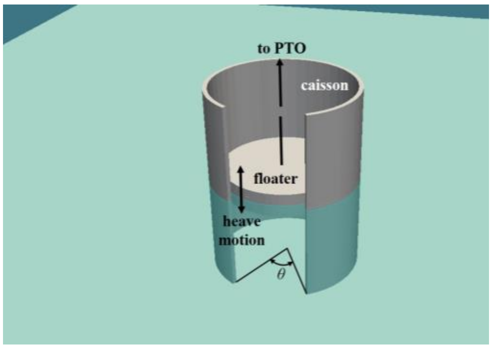


Fig. 4. The schematic of caisson-and-WEC system.

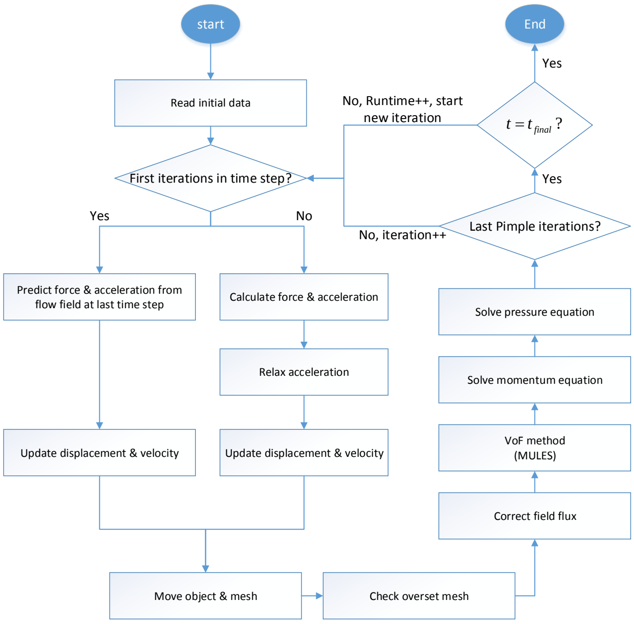


Fig. 5. The iteration process for the interaction between the floater and the waves inside the caisson.

To simplify the analysis, we assume that the only motion mode of the floater is heave and that the floater is a rigid body which does not deform under the action of hydrodynamic forces. Additionally, for comparison purposes, we also put the same WEC system in the open water without the caisson. Under the identical incoming waves, we investigate the floater motion and power generation of these two setups. Of course, we assume that the floater is also restricted to heaving motion in the open-water setup even though such an assumption does not reflect the situation in the real sea.

D. *The computation process for fluid-structure interaction*

To investigate the interaction between the floater and the waves inside the caisson, we employed the technique of dynamic meshing without topological change to handle the remeshing due to the motion of the floater. The modulus which we employed from the free OpenFOAM software is dynamicMotionSolverFvMesh. One of its features is that the floater motion is solved by using the net force derived from the non-uniform pressure distribution in the flow field. The mesh at the next time step is determined via the concept of dynamics. That is, the net force acting on the body surface is first computed by using the pressure distribution which is solved in the flow solver. Then, the position of the floater at the next time step is decided. Finally, the new mesh is obtained by solving the Laplace equation. In such a procedure, the mesh at the new time step will keep its good quality in uniformness and smoothness, rather than become badly skew due to local inappropriate mesh compression or expansion.

Furthermore, to decide the new position of the floater at the next time step, the Newmark method [17] was employed.

The iteration process for the fluid-structure interaction is shown in Fig. 5. The solution iterations at a time step comprises a big iteration loop of floater motion by the Newmark method and sub-iteration loop of hydrodynamic computation by the finite volume method. That is, in each iteration of the Newmark method to find the floater's new position at the "next" time step is inclusive of the iterations of hydrodynamic computation. Starting from the "present" time step, we compute the force acting on the floater from the pressure distribution on the body (at the "present" step) which is obtained from the flow computation. Then the acceleration of the floater is determined and its displacement and velocity decided. And the new mesh generated. Finally, the flow field at the new time step is computed under the computed displacement and acceleration of the floater. Using the new flow solution, we re-calculate the coefficients used in the Newmark method and check if they are convergent. If they are not, we have to return to the "present" time step and use the updated coefficients to determine the new position of the floater. The above process is repeated for the "present" time step till convergence of the coefficients is achieved. Only till then, the whole iteration to the "next" time step is complete and the computation can proceed to the new time step. This is a very time-consuming process.

With the addition of the floater, the mesh design becomes more complicated and the mesh number is also increased. For the system of WEC inside the caisson, the grid number is about 2.4M; for the WEC system without the caisson, it is about 2.1M.

E. The results

Fig. 6 shows the displacement of the floater CM (center of mass) under the action of the incoming wave for which the period is 13 s and wave height is 2.43 m. The motion of the WEC system in the open water has a very stable oscillation almost immediately after the wave interacts with the WEC. It oscillates between $z = 1.2$ m and $z = -0.7$ m. In contrast, the oscillation for the WEC inside the caisson does not stabilize immediately after the wave coming into the caisson. An overshoot appears first and then reaches its stable oscillation gradually. The amplitude of oscillation in this situation is much larger, from $z = 1.95$ m to $z = -1.95$ m. The oscillation amplitude is twice as large as that in the open water. In addition, comparing the two curves in Fig. 6 indicates that the wave oscillation inside the caisson synchronizes with the incident wave and there is no phase lag.

Shown in Fig. 7 is the velocity variation history of the floater CM. Due to the larger oscillation for the WEC inside the caisson, it is expected that the velocity is larger. The velocity varies between 0.6 and −0.6 m/s for the WEC in the open water, and 0.9 and −1.1 m/s for the one inside the caisson.

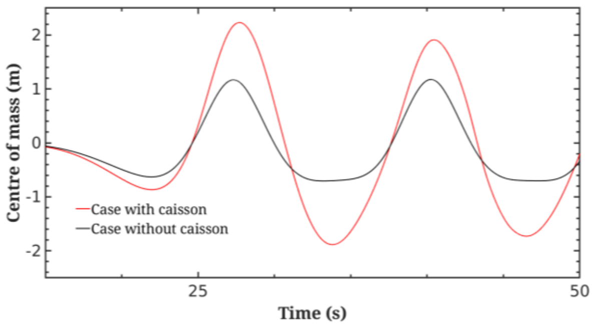


Fig. 6. Displacement of floater CM in time.

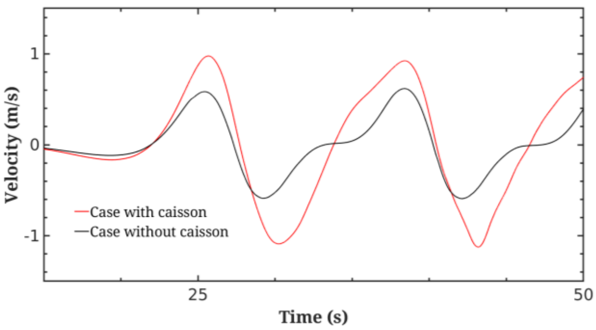


Fig. 7. Velocity of floater CM in time.

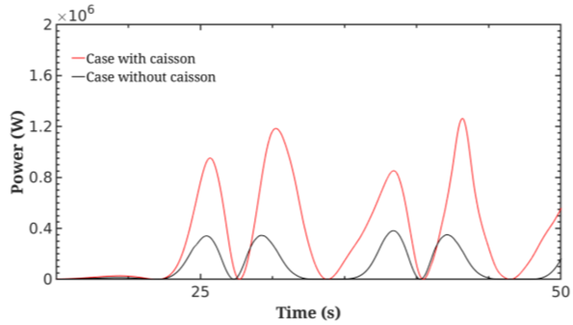


Fig. 8. Power of the PTO in time.

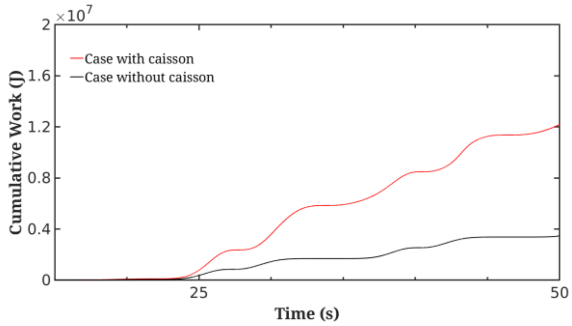


Fig. 9. Cumulative energy production of the PTO in time.

The power produced by the PTO with the present specified parameters is shown in Fig. 8. The maximum power for the WEC in the open water is about 380 kW whereas the maximum value for the WEC inside the caisson is about 1.26 MW, more than 3-fold of the former one. Of course, power generation is fluctuating due to the heave motion. To make the power generation stable relies on the design of the WEC array and PTO system which is out of the present focus. Finally, Fig. 9 shows the cumulative power generation. Up to $t = 50$ s, the total power generated is 12.2 MJ for the caisson-and-WEC system and 3.5 MJ for the WEC in the open sea. Their ratio is about 3.5.

With the parameters set up in the present study, the caisson-and-WEC system (without wave guides), the power output for a day can ideally reach 37,615 kW h. Indeed, the caisson-and-WEC system can be a possible alternative of green energy in medium wave power regions around the world.

IV. CONCLUSIONS

In the present study, we have conducted a computational investigation on the wave energy harvesting system which consists of an open caisson and a WEC. The caisson serves to amplify the wave energy density inside it and the WEC harnesses the amplified wave energy. The WEC has two important parts, the floater and the PTO system. The PTO is modelled as a damper with a constant damping coefficient.

The effect of harbour resonance of the caisson was first examined. Two kinds of caissons were designed and tested. The one with a pair of wave guides creates better harbour resonance and can amplify the wave energy density up to 8.5 times as much as that of the incident wave far upstream.

Then best condition (T = 13 s) was then employed for the investigation of the WEC power take-off. The PTO system is modelled as a damper with a constant damping coefficient of 10^6 kg/s. The results show that the amount of power generation in a period for the WEC inside the caisson with the wave guides is much larger than that for the WEC in the open water. The ratio of their energy capture is about 3.5. Compared to the 4-fold increase of wave energy inside the caisson (without WEC), the threefold increase in power generation is good. This appears to show that the present combination of the damping coefficient and floater geometry and density is not too far away from the optimal one. To optimize the WEC system, the parameters which need be considered include, at least, the form and density of the floater and the damping coefficient of the PTO. The optimal combinations are now under investigation.

The power generation for the WEC system inside the caisson with wave guides will be even more bigger since its amplification is much bigger than that of the caisson without wave guides. The computation is under way and more results will be presented in the near future.

V. FUTURE WORK

The study shows that the caisson-WEC system is a possible remedy for the sea with medium/low wave energy potential. The authors are planning the following work for further investigation. The effect of different PTO damping coefficients is under study and the best value will be found and used for designing the PTO system. The optimum form of the floater will also be examined through a series of computation and Taguchi Methods.

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