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To cite this article: C Ren *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1294** 012009

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IOP Conf. Series: Materials Science and Engineering 1294 (2023) 012009 doi:10.1088/1757-899X/1294/1/012009

Assessment of a novel PTO system for swell energy convertors using digital twin modelling

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Abstract. There is no lack of ideas and prototypes for wave energy converters (WECs). However, existing WECs are designed to extract energy from waves at normal to high frequencies and typically focus on close-to-shore steep waves and short wavelengths to gain a frequent movement of interactive components. This limits the size of the buoyancy structure and results in the need to use many generating units to achieve a high-power output. We reverse this focus in small and coastal WECs mentioned above by harvesting swell energy through the Swell Energy Convertor (SWC). SWC uses an innovative power take-off (PTO) system, which Ocean Energies AS invented. This patented crankshaft mechanism transforms the linear motion from ocean waves into rotation for rotating a generator. When combined with a large buoy structure, this PTO system allows the SWC to focus on the swells (large wavelengths and low to high wave heights) further offshore and reduce/remove the drawbacks associated with the abovementioned coastal areas. The SWC (i) focuses on the high energy swells offshore, (ii) uses large buoy structures in combination with slight vertical movement, and (iii) can optimally extract energy in any direction. This results in SWC being a far less complex system with a much higher power output than existing WECs, which will significantly lower the cost of WECs. The SWC will target the area between Greenland and Scotland, with significantly high wave energy above 60 kW/m. This paper will present the design and analysis of the proposed PTO system in the SWC. First, the PTO model and working mechanism will be described. Second, a digital model of the PTO system will also be introduced. Third, three optimal design candidates are selected and analysed further to provide a deeper insight into the PTO design. Last, discussions and planned future works are presented.

1. Introduction

Wave energy is considered one of the most promising renewable energies with vast potential that remains largely unexploited. To date, many wave energy converters (WECs) have been developed and deployed in different countries. In addition, more than a hundred projects and more than one thousand patents have been developed worldwide, as summarised in [1]. A review of the existing WEC technologies can be found in some papers [2, 3]. The numerical benchmarking study of several existing WECs can also be noticed in [4]. However, existing wave energy plants are commonly small-scaled converters [5] and designed to extract energy from the wave at normal to high frequencies near the coast [6]. Most of them fail commercially due to low power generation compared to the installation cost and high maintenance requirements. A reason for the low power generation is the geographical location of the device. Near the coast, the wave patterns are generally focused in one direction and diminished in

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amplitude in other directions. These waves also tend to break and put high loads on the structures. This means that the devices are often operating at suboptimal conditions.

To overcome the limitations of the small and coastal WECs mentioned above, this present work aims to harvest wave energy through the Swell Energy Converter (SWC). Swells often have a relatively long wavelength; long-wavelength swells carry more energy and dissipate slower than coastal waves. More importantly, the present SWC uses an innovative power take-off (PTO) system [7], as shown in Figure 1 and Figure 2, which Ocean Energies AS invented. In Figure 1, the "G," "FO," and "SF," respectively, represent the generator, floating object, and seafloor. The details of the PTO system are given in Figure 2. This patented crankshaft mechanism transforms the linear motion from ocean waves into rotation for rotating a generator. Combined with a large buoy structure, this PTO system allows the SWC to focus on the swells (large wavelength and heights) further offshore and reduce/remove the drawbacks associated with coastal areas.

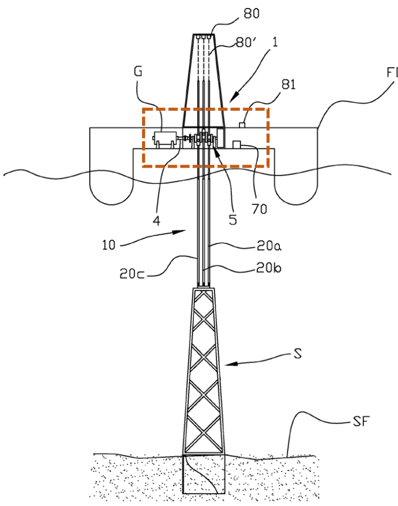

Figure 1. Swell energy converter [7]

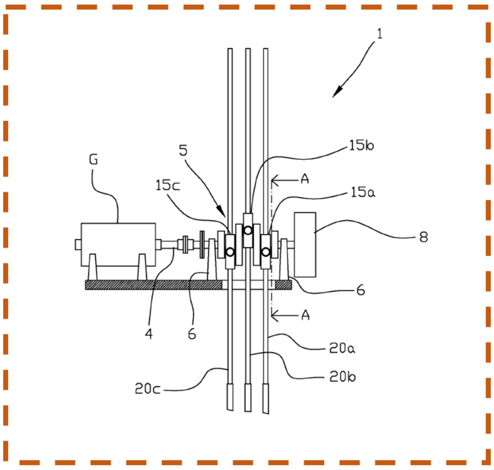

Figure 2 PTO system of SWC [7]

The present SWC will focus on the high energy swells offshore and use large buoy structures in combination with small vertical movement. This results in SWC being a far less complex system with a much higher power output than existing WECs which will significantly lower the cost of WECs. Also, the SWC will target the area between Greenland and Scotland, which has a significantly high wave energy of above 60 kW/m [8]. Scotland already has an established offshore electrical grid infrastructure that SWC can connect to.

2. PTO system working mechanism

As shown in Figure 2, the PTO mainly comprises a rotatable main shaft for driving a machinery, generator, and flywheel. Three tethers (20a, 20b, 20c) are connected to crank pins through three clutch apparatuses (15a, 15b, 15c) as depicted in Figure 3. The clutches allow gripping and releasing contact between tethers and crank pins, which can be operated by means of magnetism or hydraulics. A control system will also be developed to operate the clutch apparatuses. The operation of the clutches depends on the position of crank pins and the moving direction of the FO. Based on the movement of the FO compared to the sea floor, the operation of clutches in different positions can be classified into two cases.

2.1. An upward movement of the FO

When the floating object moves upward compared to the sea floor, the clutch apparatus located in the green portion, as depicted in Figure 4, will be set in clutch lock (CL) mode (gripping). Other clutches will be set into clutch unlock (CU) mode (releasing). The "gripping" term means that the relative movement between the tether and crankshaft is nearly zero. The "releasing" term means that the tether and crankshaft can move independently. Therefore, when in the gripping (CL) mode, any vertical movement energy of the floating object is transformed into the rotational energy of the crankshaft.

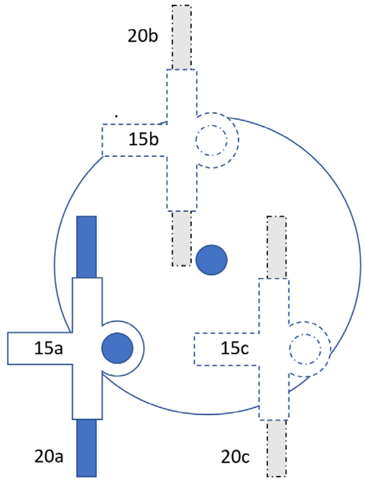

Figure 3. Three tethers and clutches in view of A-A of Figure 3

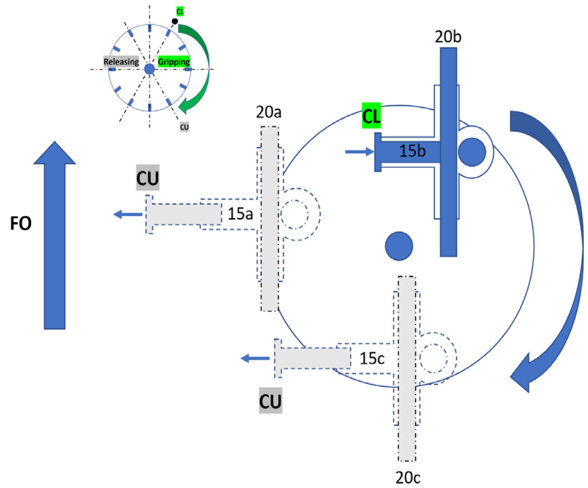

Figure 4. Upward movement of the FO

2.2. A downward movement of the FO

Similarly, when the floating object is moving downward compared to the sea floor, the clutch apparatus located in the green portion, as shown in Figure 5, will be set in CL mode. Other clutches will be set into CU mode. Depending on the up and down movement of the floating object, the switch of CL and CU mode ensures that the crankshaft can always rotate in the same direction.

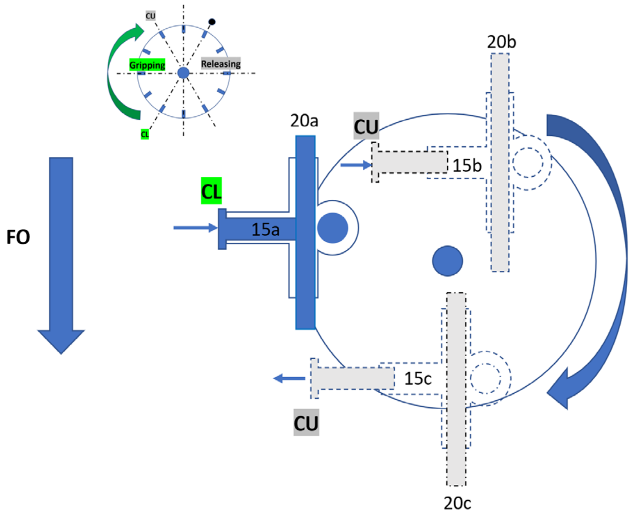

Figure 5. Downward movement of the FO

Due to this gripping and releasing configuration provided by the clutch apparatus, the crankshaft can be rotated several times during an upward movement and several times during a downward movement of the floating object. During such a rotation of the crankshaft caused by the upward or downward movement of the FO, a gripping contact will be at different positions along a longitudinal axis of the crankshaft. More importantly, this PTO system can be independent of wave amplitude and wavelength and can be installed in both shallow and deep seas. Additionally, more details of the PTO system working mechanism can be found in [7].

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3. A digital twin model of the PTO system

Based on the working mechanism of the PTO system, a digital twin model of the PTO system is created in MATLAB toolbox. The PTO digital twin model mainly comprises two parts: Hydrodynamic forces and crankshaft and tether motion. The overview of the PTO digital twin system is given in Figure 6.

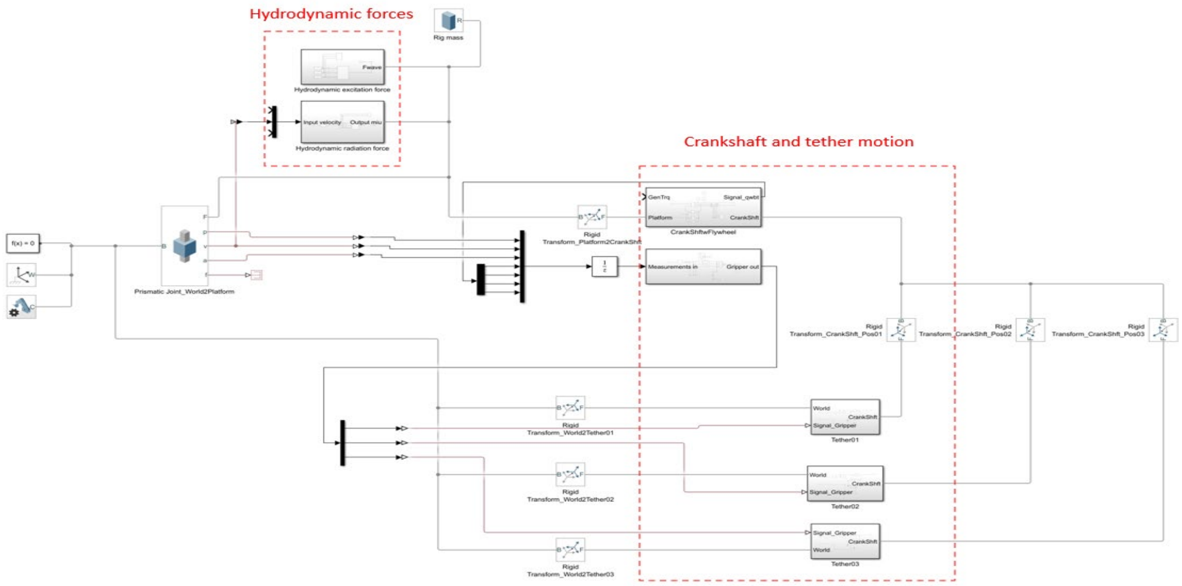

Figure 6. Overview of the PTO digital twin system

3.1. Hydrodynamic force subsystem

According to reference [9], the motion of the buoy can be formulated as follows based on Newton's second law:

$$\mathbf{M}\ddot{\boldsymbol{q}} = \mathbf{F}_{\boldsymbol{ext}} + \mathbf{F}_{\boldsymbol{r}} + \mathbf{F}_{\boldsymbol{b}} \tag{1}$$

where **M** is the inertia matrix of the oscillating body and $\boldsymbol{q}$ is the displacement from the equilibrium position. $\mathbf{F}_{ext}$, $\mathbf{F}_{r}$, and $\mathbf{F}_{b}$ are respectively excitation force, radiation force, and hydrostatic force. The radiation force can be represented as:

$$\mathbf{F}_{\boldsymbol{r}} = -\mathbf{A}(\omega)\ddot{\boldsymbol{q}} - \mathbf{B}(\omega)\dot{\boldsymbol{q}} \tag{2}$$

where $\mathbf{A}(\omega)$ and $\mathbf{B}(\omega)$ are the frequency-dependent added mass matrix and damping matrix, respectively. Normally, it is assumed that the body is constrained to oscillate only in the heave direction. Hence, the hydrostatic force is calculated as:

$$\mathbf{F}_{\boldsymbol{b}} = -\mathbf{G}\mathbf{q} = -\boldsymbol{\rho g S_w}\mathbf{q} \tag{3}$$

Where **G** is the buoyancy stiffness. $\boldsymbol{\rho}$ and $\boldsymbol{g}$ are the water density and gravity acceleration, respectively. $\boldsymbol{S_w}$ is the equilibrium water plane area of the body. Then, Equation (1) can be rewritten as:

$$[\mathbf{M} + \mathbf{A}(\omega)]\ddot{\boldsymbol{q}} + \mathbf{B}(\omega)\dot{\boldsymbol{q}} + \mathbf{G}\mathbf{q} = \mathbf{F}_{ext} \tag{4}$$

And in the frequency domain:

$$\left[-\omega^2\big(\mathbf{M} + \mathbf{A}(\omega)\big) + i\omega\mathbf{B}(\omega) + \mathbf{G}\right]\mathbf{q} = \mathbf{F}_{ext} \tag{5}$$

In this present work, the matrices **M**, $\mathbf{A}(\omega)$, and $\mathbf{B}(\omega)$ are derived from the pre-simulation results in ANSYS AQWA. The $\mathbf{F}_{ext}$ is then simulated in MATLAB based on different wave theories. In this paper, only the regular waves are investigated, which gives:

$$\eta = \boldsymbol{A_\eta} \cos(\omega t - kx) \tag{6}$$

where η is wave elevation, $\boldsymbol{A_\eta}$ is the wave amplitude, ω is the angular frequency, and k is the wave number.

3.2. Crankshaft and tether motion subsystem

Due to the excitation of the wave elevation, the floating object will go upward and downward. The movement of the floating object and the tether position will be measured in the subsystem. A control system is then developed to operate the clutch apparatuses for clutch lock and clutch unlock mode. The gripper forces provided by clutch apparatuses due to the motion of the floating object will drive the movement of the crankshaft. The gripper forces may come from different clutches due to the position of the tether and the movement of the floating object, as shown in Figure 7. In this work, it is assumed that the gripper force is constant for all the clutch apparatuses during the movement of the floating object.

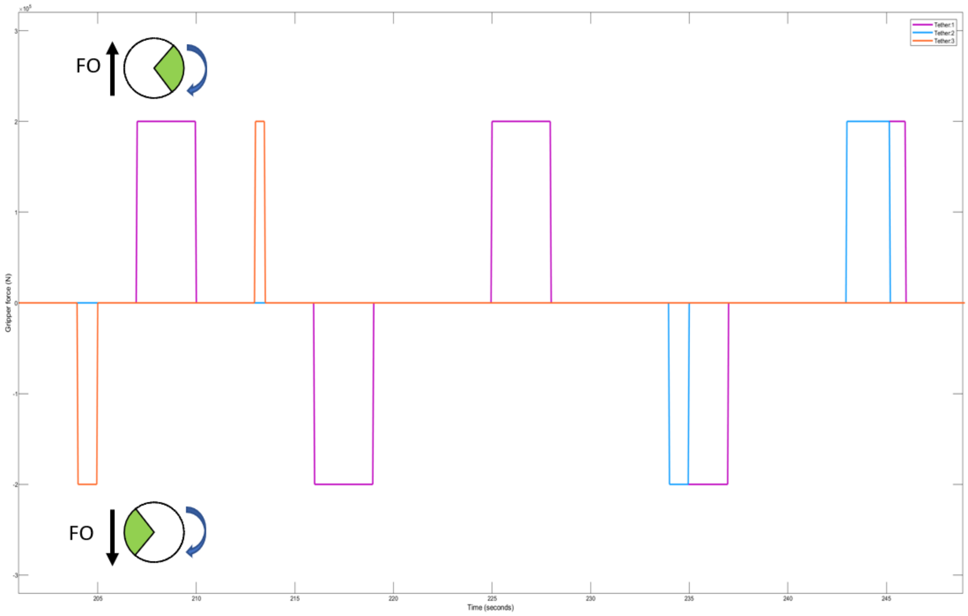

Figure 7. Gripper force from different clutches.

Additionally, to maximise the energy output, the floating object should be controlled to approach an optimum interaction between the SWC and wave. There are commonly three control strategies for wave energy converters: Reactive control, Latch control, and passive control. To simplify the modelling in this present work, a passive control system is adopted in this study.

4. Characteristic performance of the PTO system

In this part, the characteristic performances of the novel PTO system are investigated. At first, the influence of the floating object dimension is studied. The power matrix of the floating object is roughly calculated based on the Budal upper bound. The influence of the floater dimension on the power matrix is studied. Secondly, the sensitivity study of the PTO parameters is investigated. The influences of the key PTO parameters on averaged power generation are compared.

4.1. The influence of floater size on SWC power matrix calculation

In this subpart, the influence of the floater dimension is studied. The floater is assumed to be a cylinder and is semi-submerged in the seawater. The height of the cylinder floater is fixed at 10 meters, and the

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displacement of the floater is assumed at 5 m. Three different diameters (20 m, 60 m, 100 m) of cylinder floater are compared.

According to [10], for the heaving semi-submerged WECs, the WEC generated power is limited due to Budal upper bound (BUB), which is presented as follows:

$$P \leq P_A \quad \text{and} \quad P < P_B \tag{7}$$

Where P_A is known as left-hand upper bound, and P_B is the right upper bound. Figure 8 presents a schematic of Budal curves.

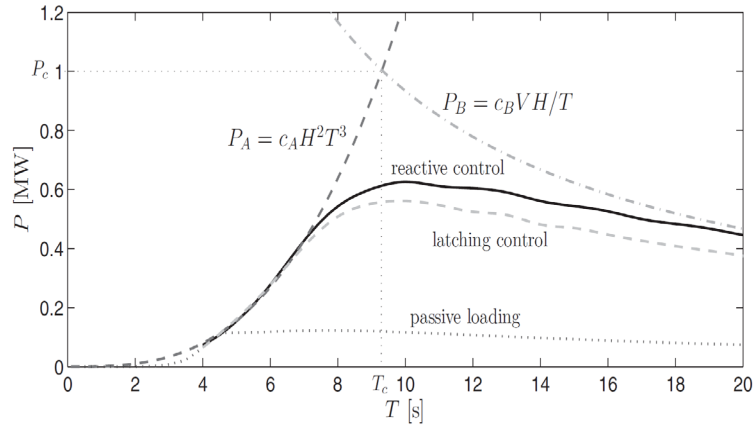

Figure 8. Budal upper bounds [10]

The equations of P_A and P_B are given as follows:

$$P_A = c_A H^2 T^3 \tag{8}$$

$$P_B = c_b V \frac{H}{T} \tag{9}$$

where H and T are, respectively, the wave height and wave period. c_A and c_B are respectively equal to:

$$c_A = \frac{\rho(\frac{g}{\pi})^3}{128} \tag{10}$$

$$c_B = \sigma \rho g \tag{11}$$

where ρ and g are seawater density and gravity constant. σ equals to $\pi/4$ in this study. As shown in Figure 8, the PTO control system greatly influences the average power generation. Typically, the ratio of the maximum absorbed power P_{max} to the intersection-point power P_c for each control strategy roughly follows:

$$\frac{P_{max}}{P_c} \begin{cases} 0.6 & for\ reactive\ \ control \\ 0.5 & for\ lathing\ control \\ 0.1 & for\ passive\ control \end{cases} \tag{12}$$

Based on the assumption of the passive control in this work, the power matric of different floater dimensions can be calculated, as shown in Figure 9 - Figure 11. With the increased floater dimension, (1) the WEC tends to have higher power density in the longer wave period. Also, (2) the left-hand upper (P_A) will affect the WEC power matrix calculation more. Additionally, because P_A is size independent, the left part (T_p:5-16s) of the power matrix of 60m and 100m diameter floater is nearly the same. (3) The highest power density will increase will the increase of floater size.

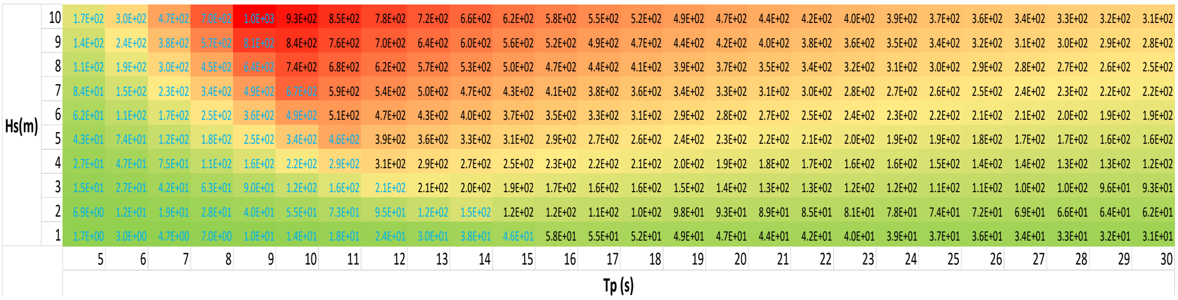

Figure 9. Floater power matric with a diameter equal to 20 m

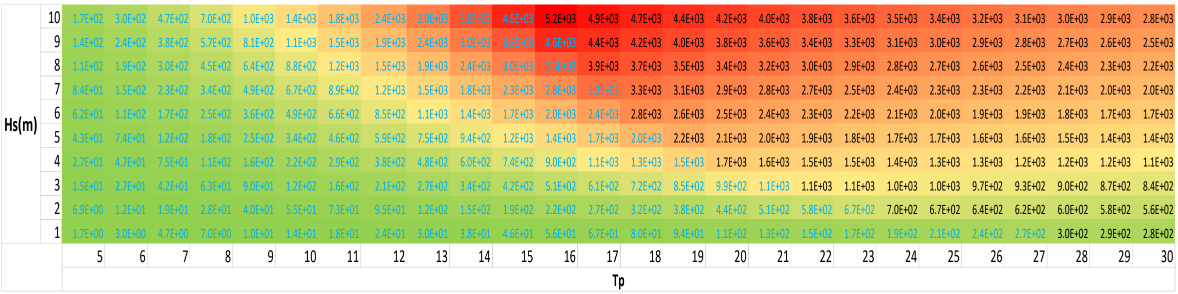

Figure 10 Floater power matric with a diameter equal to 60 m

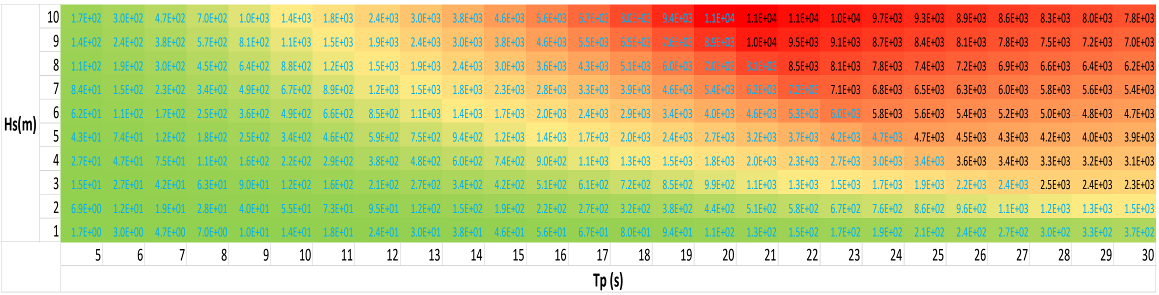

Figure 11. Floater power matric with a diameter equal to 100 m

However, it does not mean that the larger WEC is better. Considering the economic cost and ocean wave conditions, the WECs should be optimised based on different sites. In this work, two different sites, shown in Figure 12, demonstrate the influence of floater size and ocean wave conditions on WEC power generation. The wave statistics are given in Figure 13 and Figure 14 [4].

Figure 12. Sites where wave data statistics were taken.

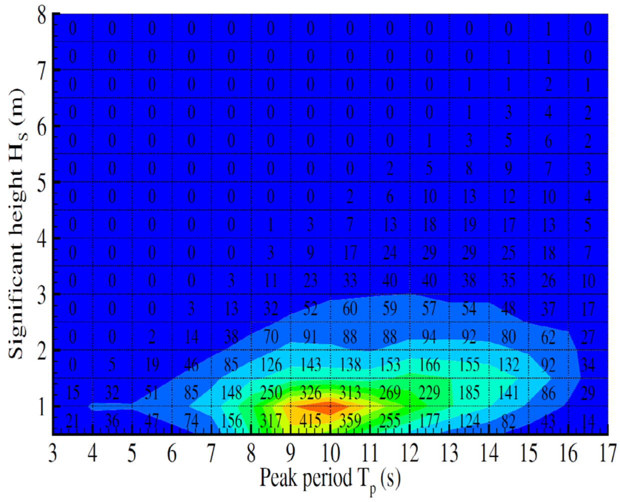

Figure 13. Scatter diagrams of wave statistics in SEM-REV [4]

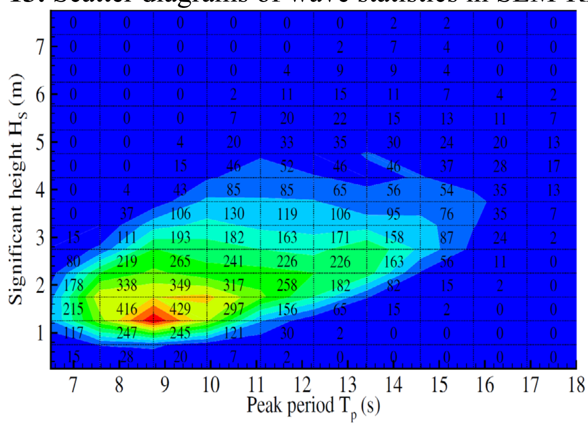

Figure 14. Scatter diagrams of wave statistics in Lisbon [4]

The average annual power generation can be roughly estimated based on the SWC power matrix and the wave data statistics. The results are given in Table 1 and Figure 15. As shown in Table 1 and Figure 15, in the same site, increasing the floater diameter within a certain size can effectively increase average power generation. However, when the floater is beyond a certain size, the floater diameter increase will not influence the power generation. More importantly, it is noticed that the different sites will have a great influence on power generation. As shown in Figure 15, site 2 can generate two times more power than site 1.

Table 1 Influence of floater size and ocean site

Site 1: SEM-REV	
Floater diameter (m)	Average power generation (kW)
20	70.74
60	102.13
100	102.13
Site 2: Lisbon	
Floater diameter	Average power generation (kW)
20	130.74
60	223.13
100	223.13

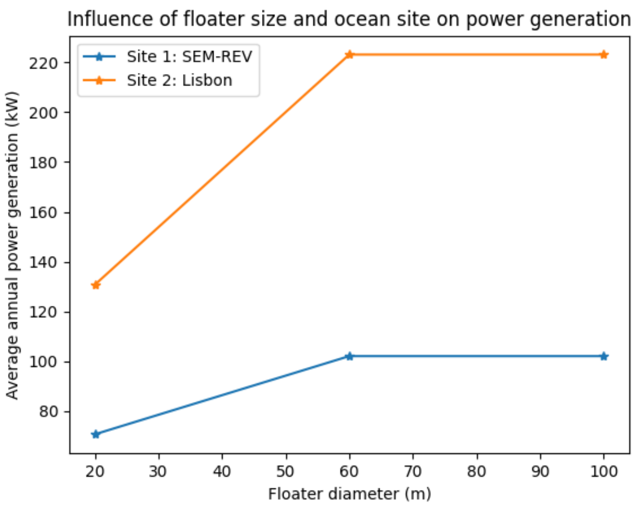

Figure 15. Influence of float size and ocean site on power generation

4.2. Performance study of the PTO system

The power generation of the WECs is not only influenced by the floater size and ocean wave condition but also by the PTO system. In the previous subpart, the influence of the floater size and ocean wave is studied. In this subpart, the influence of the PTO system parameters is considered. Four key parameters of the PTO system are investigated. They are, respectively diameter of the crankshaft (Dc), the inertia of the flywheel (I), the gripper force (F) and the generator damping coefficient (Cd). The results are summarised in Table 2. For the crankshaft diameter (Dc), it has an important influence on the averaged power generation. As depicted in Figure 16, the power generation will also increase with the increase of Dc. Contrary to the crankshaft diameter, the flywheel inertia seems to have a very limited influence on the power generation, as shown in Table 2 and Figure 17. With the change in flywheel inertia, the power generation is nearly the same. As for the gripper force, as shown in Figure 18, the increase of gripper force will significantly increase the power generation. It means that under the same wave excitation, the PTO system provides a higher gripper force that will generate more power. Additionally, with the increase of the generator damping coefficient, the SWC power generation will decrease a lot depicted in Figure 19. It is clear that Dc, F, and Cd have an important influence on power generation. To design the SWC, these three parameters need to be carefully chosen.

Table 2 Parametric study of the PTO system

Influence of Crankshaft diameter	
Dc (m)	Averaged power generation (kW)
2	0.97
4	1.80
6	6.63
Influence of flywheel inertia	
I (Kg*m^2)	Averaged power generation (kW)
2e6	0.97
6e6	0.97
1e7	0.97
Influence of Gipper force	
F (N)	Averaged power generation (kW)
2e4	0.13
6e4	0.97
1e5	5.43

Influence of Generator damping coefficient	
Cd (N*M/(rad*s))	Averaged power generation (kW)
2e5	0.97
6e5	0.38
1e6	0.11

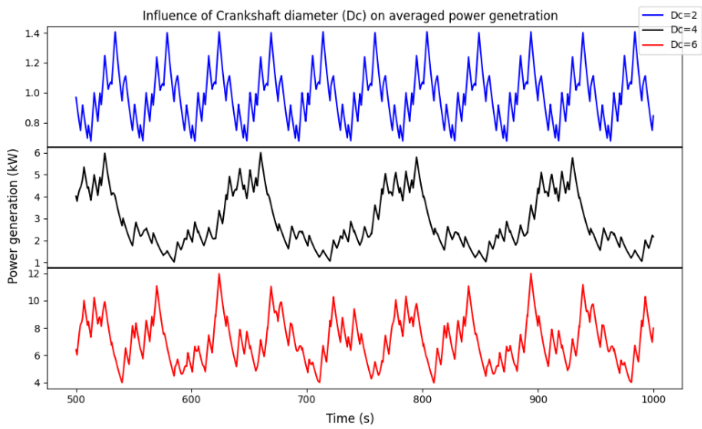

Figure 16. Influence of crankshaft diameter.

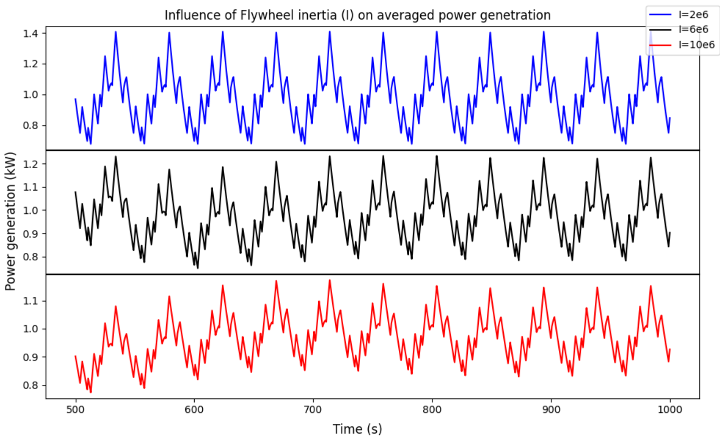

Figure 17 Influence of flywheel inertia.

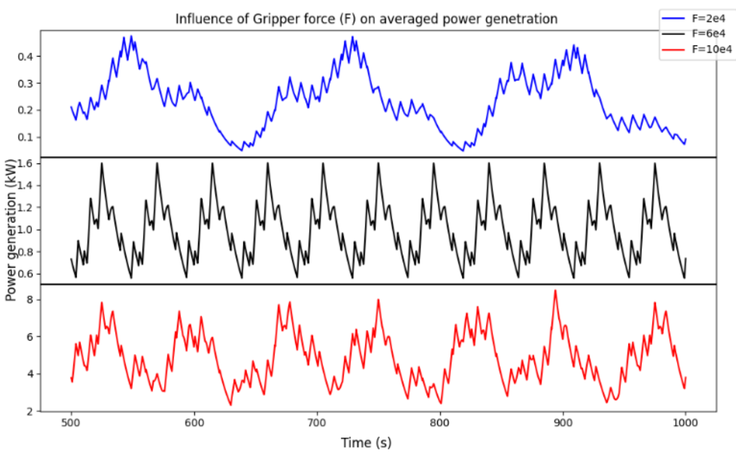

Figure 18. Influence of Gipper force.

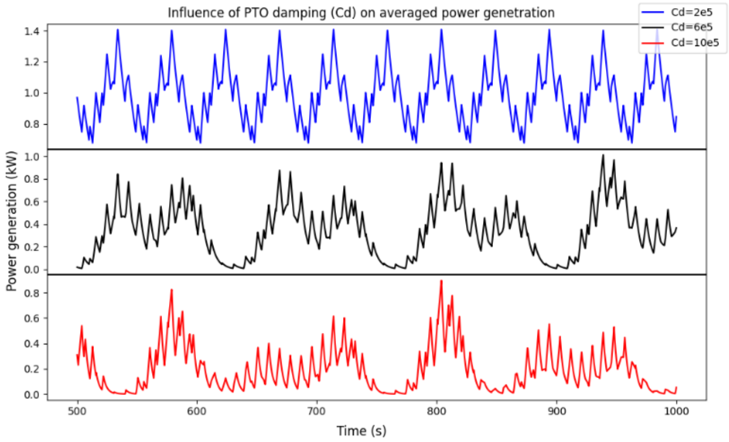

Figure 19. Influence of Generator damping coefficient.

5. Conclusion and future works

In this paper, a novel PTO system is presented to harvest energies from ocean waves (or swells). The novelty of the PTO system is to transform linear motion from ocean waves into rotation through a rotating shaft. The basic working mechanism of the novel PTO system is briefly introduced. A digital twin model of the PTO system is also created based on the MATLAB toolbox. The characteristic performance of the PTO system is also investigated. The results show that:

Firstly, from the study of floater size, it is noticed that the SWC power matrix tends to have power density in the long wave periods with the increase of the floater size. Also, with the increase of the floater size, the left-upper bound of the power limit will play a dominant role in the power matrix calculation. Additionally, based on the study of two different sites, the influences of ocean sites are important, and can even double the annual average power generation. Also, increasing floater size within a certain size in the same ocean site will effectively increase average power generation. However, when the floater is beyond a certain size, the floater diameter increase will not influence the average power generation. It is because, with the increase of the floater size, the left-upper bond of the power limit will play a dominant role in the power matrix, which is size-independent. The floater size needs to be optimised considering the economic cost and the specific ocean site.

Secondly, the parametric study of the PTO system is carried out based on the developed digital model. It is noticed that the crankshaft diameter, gripper force, and generation damping coefficient will play an important role in the SWC power generation. However, the flywheel inertia has little influence on the power generation, which can be ignored in the future optimisation process. More attention should be paid to the other three parameters for the parameter optimisation process.

Finally, the present work only focuses on the regular waves, and a passive control model is used in the PTO system. In the future, the influence of irregular waves will also be investigated. More importantly, based on the Scotland and Greenland ocean wave data, the optimal size of the floater will be investigated. The latch control and reactive control will also be applied to the novel PTO system, which will significantly improve the average power generation of the system.

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Financial support from RFF Rogaland (Project: 336822 – RFFROGALAND Støtte fra andre enn Forskningsrådet Regionalt kvalifiseringsprosjekt Swell Energy Convertor – Proof of Principle Study for PTO system) is acknowledged.

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