Modelling of Unidirectional Oscillating Buoy Wave Energy Converter Based on Direct Mechanical Drive System Under Irregular Wave

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Abstract. The development of wave energy converters (WEC) is increasing over time with various designs. The need for a WEC design that emphasizes the level of simplicity, portability, and closeness of its implementation to the nearshore is quite interesting to discuss. One of the WECs that can meet these criteria is oscillating buoy based on a direct mechanical drive system. This research proposes the concept of oscillating buoy WEC based on a direct mechanical drive system, which is designed with a unidirectional gear system to be able to generate energy both in the upward and downward wave phases. The WEC is also making to produce high rotation on the output side from the small motion of the buoy, especially in the heave direction. Predicting the power generated by this concept is very interesting because up to now, there has not been sufficient analytical model to estimate the power generated by oscillating buoys WEC based on a direct mechanical drive system, especially under irregular waves. In this work, an analytical method is conducting to describe the interaction between the model and irregular waves from the JONSWAP model. Model interaction is simulating numerically using the MATLAB program. The buoy translational motion of the model in the heave direction, which is converting to electric power by increasing the rotation of the gearbox and the energy stored in the flywheel, can produce significant output power. In the future, the proposed model can be used to develop more feasible and efficient models of wave energy converters.

1. Introduction

Ocean waves accommodate abundant resources of renewable energy that can occupy over two-third of the overall earth’s surface. Theoretically, this energy has a roughly usable power of up to 32 TW/year worldwide [1] and 2 TW nearshore [2]. Thus, this potency can efficiently supply a significant portion of the world’s electricity consumption. Besides wave energy offers clean, safe, and sustainable energy source, it also has several advantages comparing with other alternative renewable energies, such as solar and wind energy as ocean waves have a much higher energy density [3], more predictable [4], and more nearly continuous in a day [5]. By the amount of power that able to be harnessed, ocean wave energy becomes a brilliant breakthrough in the future to eliminate carbon emissions due to over utilizations of fossil fuels and become an essential part of the demand for non-polluting electricity for human social development. Since wave energy can handle the needs of carbon emission and electricity, the development of wave energy converters (WEC) has become the most substantial aspect in the effort to generate energy from ocean waves [6].

Up to now, WEC has developed with various designs, both on a small scale and large scale. From these designs, many different techniques to extract wave energy into electricity also have been studied in recent years. One of the most developed WEC is an oscillating buoy type that reaches 45% of the implemented WEC in the world [7]. The oscillating buoy is very interesting to develop because of several advantages such as being able to absorb wave energy over a vast range [8], having higher
efficiency [9], a relatively simple design [10], and more suitable for areas that have low energy density along the coastline [11].

In general, extracting ocean wave energy requires a specific power take-off (PTO) method with the most common are hydraulic oil converter and direct electrical drives system. However, in the hydraulic oil converter system, oil leakage is an aggravating problem and has a negative impact in the context of polluting the marine environment [12]. Meanwhile, the problems of a direct electrical drive system are the protection of the electrical components and the arrangement of the air gap that requires a complicated design [13]. Consequently, making WEC from the two previous systems is very expensive because of the complexity of their design. Therefore, mechanical gear transmission or direct mechanical drives system can be an alternative method to convert wave energy efficiently with the simplicity of the system and the affordability of manufacturing costs [14] [15]. This system also can be constructed for portable design, making it easier to repair.

For these reasons, this paper focuses on the concept of an oscillating buoy wave energy converter based on a direct mechanical drives system called UNOWEC (Unidirectional Oscillating Buoy Wave Energy Converter). This design is equipped with a unidirectional gear system to be able to generate energy both in upward and downward wave phases. UNOWEC is also making to produce high rotation on the output side from the small motion of the buoy, especially in the heave direction. To assess the performance of this WEC in real seas, the analysis of the WEC under irregular waves is necessary [16]. Previously, there has not been an adequate analytical model to predict the power generated by oscillating buoys WEC based on a direct mechanical drives system, especially under irregular waves. So, it will be more accurate to estimate the harnessed power by simulating UNOWEC under dynamic wave conditions.

The paper is organizing as follows: Section 2 gives a brief description of the proposed WEC and the methodology to simulate the power extraction. In section 3, the results of the spectrum characteristic, buoy displacement, unidirectional system behavior, and captured power are presenting and discussing. Finally, the conclusions are drawing in section 4.

2. Methods and material

2.1. Wave Mathematical Model

Assessing the performance of a WEC in real seas condition becomes a necessary aspect for power extraction and motion behavior analysis purposes. To describe the characteristics of real sea conditions, an approach can be made through numerical simulations using assumptions of irregular waves theory. Since the irregular wave is considering as the superposition of a series of sinusoidal waves, it assumes that the wave heights are small compared to the wavelength [17]. Therefore, the wave elevation (in the time domain) of a long-crested irregular sea, propagating along the positive x axis, can be written as the sum of a large number of regular wave components (in the frequency domain) with different amplitude, frequency, and phases as Equation 1 [18].

\[
\zeta(t) = \sum_{n=1}^{N} \zeta_m \cos(\omega - k_n x + \xi_n)
\]  

in which \(\zeta_m\) is wave amplitude component (m), \(\omega\) is circular frequency component (rad/s), \(k_n\) wave number component (rad/m), \(\xi_n\) is random phase angle component (rad).

To express wave energy in real sea waves, usually using the wave energy spectrum \(S(\omega)\). This parameter is a distribution of the wave energy of a given location as a function of the wave frequency band \((\omega)\) [19]. From that, it has found that the wave amplitude component represented as Equation 2.

\[
\zeta = \sqrt{2S(\omega)\delta\omega}
\]

Energy stored in a wave per unit sea surface area \((\overline{E})\) is the sum between kinetic and potential energy that formulated by Equation 3.

\[
\overline{E} = \frac{1}{2} \rho g \zeta^2
\]
where $\rho$ is the water density about $1025 \text{ kg/m}^3$, and $g$ is the gravity acceleration about $9.81 \text{ kg/s}^2$.

Thus, the average rate of energy flux across a fixed control surface is the product of the energy density and group velocity. This parameter called the wave power per unit wave-front length that given by Equation 4.

$$\frac{dE}{dt} = v_g \bar{E}$$  \hspace{1cm} (4)

where $v_g$ is wave group velocity, calculated by the Equation 5 [20].

$$v_g = \frac{1}{2} \left(1 + \frac{2kd}{\sinh 2kd}\right)$$  \hspace{1cm} (5)

where $d$ is the water depth and $k$ the wave number.

If it is assumed that the desired location in deep water, the water depth will larger than half of the wavelength ($d/L \geq 0.5$). So, Equation 5 can be expressed by Equation 6.

$$v_g = \frac{\omega}{2k} = \frac{g}{4\pi f} = \frac{gT}{4\pi}$$  \hspace{1cm} (6)

Hence, the wave power in deep water is presented by Equation 7.

$$\frac{dE}{dt} = \frac{1}{8\pi} \rho g^2 \bar{E}^2 T$$  \hspace{1cm} (7)

By substituting Equation 2 to Equation 7, it will produce the wave power corresponding to the wave frequency band in Equation 8.

$$\Delta \left(\frac{dE}{dt}\right) = \frac{1}{8\pi} \rho g^2 \left[2S(\omega) \delta \omega\right] \frac{2\pi}{\omega} = \frac{1}{2} \rho g^2 S(\omega) \frac{\delta \omega}{\omega}$$  \hspace{1cm} (8)

Subsequently, the total average wave power shown by Equation 9.

$$\frac{dE}{dt} = \frac{1}{2} \rho g^2 \int_0^\infty S(\omega) \frac{\delta \omega}{\omega}$$  \hspace{1cm} (9)

Relationships with statistics can be found from computing the moments of the area under the spectrum. The spectral moment is formulated by Equation 10.

$$m_n = \int_0^\infty \omega^n \cdot S(\omega) \cdot \delta \omega$$  \hspace{1cm} (10)

where $m_n$ denotes the $n^{th}$ order moment. For $n = 0$ and $n = -1$, Equation 10 rewritten as:

$$m_0 = \int_0^\infty S(\omega) \delta \omega$$

$$m_{-1} = \int_0^\infty \frac{S(\omega)}{\omega} \delta \omega$$  \hspace{1cm} (11)

$m_0$ is the integral of the wave energy spectrum and $m_{-1}$ is the first negative moment of the wave energy spectrum. Since the energy period ($T_e$) and the significant wave height ($H_s$) is expressed as:

$$T_e = 2\pi \frac{m_{-1}}{m_0}$$

$$H_s = 4\sqrt{m_0}$$  \hspace{1cm} (12)
the wave power resource in irregular waves \( P_{\text{res}} \) can be calculated by Equation 13.

\[
P_{\text{res}} = \frac{dE}{dt} = \frac{1}{2} \rho g^2 \left( \frac{H_s}{2\pi} \right) \left( T_e \right) = \frac{1}{2} \rho g^2 \left( \frac{H_s^2}{16} \right) \left( T_e \right)
\]

This power in W/m unit. Thus, the wave energy capture width, \( W \) (in meter), in irregular waves, can be defined as:

\[
W = \frac{P}{P_{\text{res}}}
\]

where \( P \) is captured power by WEC system. Therefore, the absorption efficiency of the WEC device is written by:

\[
\eta_b = \frac{W}{B}
\]

2.2. UNOWEC Description and Device Operation

Generally, WEC technology captures the energy contained in ocean waves and uses it to generate electricity. There are three main categories of WEC [12]:

(i) Oscillating water columns: WEC concept that use trapped air chambers in a water column to drive a mechanical turbine;

(ii) Oscillating body converters: WEC with floating or submerged concept that uses the wave motion (up/down, forward/backward, side to side) to generate electricity;

(iii) Overtopping converters: WEC concept that use a reservoir or dam to create a head and subsequently drives turbines underneath it.

Of these types, UNOWEC belongs to the oscillating buoy type that harnesses the heaving motion due to the wave energy and adopts a direct mechanical drive system concept. UNOWEC uses an oscillating buoy system that undergoes reciprocal movement along with the wave motion, and this motion is converted to mechanical energy by gear combination. Then, the generator converts mechanical energy into electrical energy.

In Figure 1, the conceptual design of UNOWEC can be illustrated. When an incoming wave reaches the UNOWEC buoy, it is displaced throughout the z-axis direction a distance equal to the wave amplitude. The lever is pivoted at certain point; so that the vertical movement caused by the incoming wave produces a rotational movement of the lever. This rotation generates an angle \( (\theta(t)) \) measured between the still water level and the lever position. This angle is a function of time and the incoming wave amplitude. By interconnected between the lever and generator, the yield motion will converted to the electric power. The design of UNOWEC shown in Figure 1 allows its location at the shore and can be installed above the sea (in shallow water), integrated in a breakwater, in a dam or fixed to a cliff. The main advantage of this WEC is its ease of maintenance and installation since in most cases the location is accessible [21]. Moreover, they do need neither mooring systems nor a long length of sea cable to connect the WEC to the electric grid. However, at the shoreline, waves contain less energy because of their interaction with the seabed. If UNOWEC desired to be able to extract more energy, it would install in the deep-water sea. Since the deep-water sea generally has a far distance from the shoreline, it requires a floating structure and submarine cables for electrical power transmission. Therefore, selecting an
energy extraction location that is adjusting to the costs and benefits of future investment is the key to the successful WEC project.

![Diagram of UNOWEC](image.png)

**Figure 1.** The conceptual design of UNOWEC

UNOWEC mechanism rests on the direct mechanical drive system that is equipping with a lever pair and gear configuration. UNOWEC system also uses a unidirectional rotation concept that is generated both in the upward and downward wave phases. From these cycles, the buoy will generate a heaving motion ($z$). The change of this motion in one direction was initiated by the inverse gears and transmitted it to sprocket and freewheel configuration. This concept only obtains a small heave motion, so this motion is boosting by the gearbox system. Next, this rotation is forwarding to the pulley that is connected to the generator by the van belt. Flywheel allows the system rotation is more continuous and also stores the rotational energy for enhancing the performance of the generator.

### 2.3. UNOWEC Motion in Irregular Wave

Generally, irregular waves are composed of superimposed sine waves having various heights and periods that pass a site randomly in time and are distributed randomly in space. When either a floating structure or a fixed compliant structure is locating at an ocean site, each component of the wavefield will produce a force on the structure that can result in a motion. In oscillating buoy WEC, this motion is very crucial to generate electricity. For the UNOWEC assumption, it is considering that the deep-water buoy is moving lucratively in a random sea. The notation for this buoy is sketched in Fig 2. The value of water depth is assumed in infinity ($h = \infty$). Assume that the forcing function is due to random waves. The illustration also assumes that the wavelength components are an order of magnitude greater than the radius ($R$) of the buoy. Because of the latter assumption, $kR < 0.3$ and the vertical wave-induced force on the buoy is quasi-hydrostatic [17]. Also, from Fig 2 the movement characteristic of the buoy can be represented as a mass-spring-damper system with the equation as follows:

\[(m + a)\frac{d^2z}{dt^2} + b\frac{dz}{dt} + cz = F_z(t)\]  \hspace{1cm} (16)

Therefore, the value of each parameters like added mass ($a$), damping ($b$), and spring ($c$) coefficient can be found. To ease the calculation, added mass is assumed not affected by wave frequency, so it is simply taken as:

\[a \approx \frac{2}{3} \rho \pi R^3\]  \hspace{1cm} (17)
while the damping coefficient is formulated by:

$$b \geq 0.1 \rho \pi R^3 \omega$$  \hspace{1cm} (18)

the added mass and damping coefficient value is valid for $0 < kR < 0.01$, where $k$ is the wave number. Because the cross sectional area of the buoy is a circle, the value of spring coefficient is formulated by:

$$c = \rho g \pi R^2$$  \hspace{1cm} (19)

The natural period and critical damping for this system is given by:

$$T_n = \frac{2\pi}{\omega_n} = \frac{2\pi}{\sqrt{\frac{c}{m+a}}}$$  \hspace{1cm} (20)

$$\beta_c = 2\sqrt{(m+a)c}$$  \hspace{1cm} (21)

By substituting Equation (17), (18), (19) to the Equation (16), the equation of mass-spring-damper system completely is written by [17]:

$$\left( m + \frac{2}{3} \rho \pi R^3 \right) \frac{d^2z}{dt^2} + \left( 0.1 \rho \pi R^3 \omega \right) \frac{dz}{dt} + (\rho g \pi R^2)z = \Re(z)[F_\omega e^{-i\omega t}] \Rightarrow \Re \left( \rho g \pi R^2 \frac{H}{2} e^{-i\omega t} \right)$$  \hspace{1cm} (22)

In this equation, the notation $\Re$ is used to identify the real part of the term. Therefore, the steady state solution of Equation (22) is given by:

$$z = \Re[Z(\omega)e^{-i\omega t}] = \frac{1}{2}[Z(\omega)e^{-i\omega t}] + [Z^*(\omega)e^{i\omega t}]$$  \hspace{1cm} (23)

$Z(\omega)$ is the frequency-dependent complex heaving amplitude and $Z^*(\omega)$ represents its complex conjugate. The combination of Equation (22) and (23) yields the following expression for the complex heaving amplitude:
\[ Z(\omega) = \frac{F_w}{\rho g \pi R^2} \left( 1 - \frac{\omega^2}{\omega_c^2} \right)^{-i0.2} \frac{\omega \rho w \pi R}{\omega_c} = H(\omega) \frac{F_{zo}}{\rho g \pi R^2} = H(\omega) \frac{H}{2} \]  

where \( H(\omega) \) is called the amplitude response function. The function is also known as the admittance, the frequency response function, and the harmonic response function [17]. It can be seen that the amplitude response function is complex part and the real part is the wave height. From Equation 24, the \( H(\omega) \) is formulated by:

\[ H(\omega) = \frac{1}{\left( 1 - \frac{\omega^2}{\omega_c^2} \right)^{-i0.2} \frac{\omega \rho w \pi R}{\omega_c} \left( 1 - \frac{\omega^2}{\omega_c^2} \right)^{-i0.2} \frac{\omega \rho w \pi R}{\omega_c}} \]  

Equation 24 can be solved using the combination between statistical equations and spectral density. This combination yields mean-square amplitude response of the buoy as [17]:

\[ Z^2 = Z_{rms}^2 = C \int_0^\infty S(\omega) \left| H(\omega) \right|^2 d\omega \]  

\[ H_{abs}(\omega) = \left| H(\omega) \right|^2 = H(\omega) \left| H^*(\omega) \right| \]  

\( H^*(\omega) \) is the conjugate of the amplitude response, \( S(\omega) \) is the spectral density of the wave field in frequency domain, and \( C \) is a coefficient that depends on the relationship between the spectral density and the mean-square of the wave height. The value of this coefficient for JONSWAP spectral formula is 8 (assumed as same as Pierson-Moskowitz spectrum) [22] and this spectra also formulated by [23]:

\[ S_f(\omega) = (1 - 0.287 \ln \gamma) H_t^2 \frac{5 \omega_p^4}{16 \omega^5} e^{-1.25 \left( \frac{\omega_p^2}{\omega} \right)^4} \gamma^x \]  

\[ a = \exp \left( - \frac{(\omega - \omega_p)^2}{2 \sigma^2 \omega_p^2} \right) \]  

with \( \sigma \) value is 0.07 for \( \omega \leq \omega_p \) and 0.09 for \( \omega > \omega_p \).

From the Rayleigh assumption, the equivalent value of \( H_{avg} \) is expressed by [24]:

\[ H_{avg} \equiv 0.886 H_{rms} \equiv 0.626 H_s \]  

Then, the relationship of the significant, peak, modal, mean, and root-mean-square wave periods is also given by: [17]

\[ T_s \equiv 0.946 T_p \equiv 1.075 T_o \equiv 1.104 T_{avg} \equiv 1.063 T_{rms} \]  

UNOWEC also use a flywheel that can store energy and also smooth the output power produced [25]. To be able to do this, the flywheel must have a certain rotational inertia (\( J \)) specifically chosen for its application. Because rotational inertia depends on the size, shape, and mass of the rotating object, the value of it can be configured according to these three parameters. Since the solid cylindrical shape is used for a flywheel, the power equation that can be stored by the flywheel is:

\[ P_f = \frac{dE_f}{dt} = \tau_f \omega_f = J_f \alpha_f \omega_f \]  

\[ J_f = \frac{1}{2} m_f R_f^2 \]  

with \( m_f \) is the flywheel mass and \( R_f \) is the flywheel radius. Meanwhile, the value of velocity and acceleration of the flywheel (\( \omega_f \) and \( \alpha_f \), respectively) is obtained from:
\[ \omega_f = \frac{\alpha_f R_l}{L_l} \alpha_f = \frac{\partial \omega_f}{\partial t} \]  

(34)

where \( L_l \) is the UNOWEC lever length and \( \omega_i \) is the wave frequency in random sea.

3. Result and discussion

To approve the theoretical equation that mentions in the former part, some value of wave and buoy parameters are giving in Table 1. As explained earlier, the main objective of this study was to determine the power characteristics obtained by UNOWEC under irregular wave conditions. First of all, it is necessary to know the reference irregular waves used. In this study, random waves generating from the JONSWAP spectrum in the form of time series were manipulating by MATLAB. The value of significant wave height \( (H_s) \) is set to 1.5 m and the period \( (T_p) \) is 6 s. These data are used as program inputs to produce an irregular wave graph in the time series that represents the wave condition. This input data is analyzing by Rayleigh distribution. Also, the wave periods that make up the JONSWAP spectrum are assumed to be in the range of 0.5 – 2.5 rad/s. For a deep-water condition, the ratio between water depth and wavelength is more than 0.5, so the value of \( d \) is assuming as infinity. Moreover, it is assuming that the component wavelengths are an order of magnitude greater than the radius \( (R) \) of the buoy.

| Wave parameters                      | Symbol | Value   |
|--------------------------------------|--------|---------|
| Significant Wave Height              | \( H_s \) | 1.5 m  |
| Peak Spectrum Period                 | \( T_p \) | 6 s    |
| Gravitational Acceleration           | \( g \) | 9.81 m/s² |
| Water Density                        | \( \rho \) | 1025 kg/m³ |
| Water Depth                          | \( d \) | ∞      |
| Frequency Range                      | \( \omega_i \) | 0.5 – 2.5 rad/s |

| UNOWEC Components Dimension          | Symbol | Value   |
|--------------------------------------|--------|---------|
| Buoy’s Diameter                      | \( D \) | 1 m    |
| Buoy’s Height                        | \( h_b \) | 1 m |
| Buoy’s Mass (from displaced water)   | \( m \) | 805 kg |
| Buoy’s Draft                         | \( h_o \) | 1 m   |
| Lever Length                         | \( L_l \) | 2 m   |
| Flywheel Inertia                     | \( J_f \) | 100 kg.m² |
| Generator Efficiency                 | \( \eta_g \) | 0.9 |

By inputting the parameters, the characteristic of the time series irregular waves from the JONSWAP spectrum is showing in Figure 3. The time-series data of the simulation result is obtaining from the sum of a large number of the regular wave components, each with its frequency, amplitude, and phase. The simulation result shows that the generated data from the assumed spectral density gives well agreement. The characteristic between measured and theoretical analyses yield a good trend. From this result, the time-series data is also knowing as wave elevation that can be differentiated to wave velocity for the first differentiation and wave acceleration for the second differentiation. It means that the wave velocity and acceleration are also acquired from the summing waves, as explained before. Thus, the average wave power resources can be obtained by multiplying sea surface wave energy and wave group velocity that yields characteristics as shown in Figure 4. The resulting power obtained is around 12.9 kW/m in which this value is average potential to be utilized \( (P_{res}) \).
The extracted power from the wave depends on the shape and width of the buoy. For simple calculation, the buoy shape is a vertical cylinder like in Figure 2, while more buoy shape in captured power efficiency can be explored in [8]. The power resource roughly can be converted by buoy width by means in a vertical cylinder depends on its diameter. Technically, from these parameters, it will happen the interaction between wave elevation and buoy movement in the heave direction. The heaving motion part is obtaining from the absolute amplitude response. By using the equations in part 2, the added mass, critical damping, and natural period value are 268.34 kg, 5809.34 kg/s, 2.31 s, respectively. From these values, the absolute amplitude response in Equation 27 become:

$$ H(\omega) = \frac{1}{\left(1 - \frac{\omega^2}{7.36}\right) + \frac{\omega^4}{2.6 \times 10^{-4}}} $$

(35)

For the next step, the simple equation of absolute amplitude response in Equation 35 is multiplied by JONSWAP spectrum in Equation 28 to get the mean-square amplitude response in Equation 26. Consequently, this calculation will obtain the heave amplitude that compared to the wave elevation as as shown in Figure 5. It can be seen that the heave amplitude on the buoy experiences heave amplification because it is more dominant with a value greater than the wave elevation, on average. Moreover, the range of input frequency between 0.5 – 2.5 rad/s yields vertical motions dominated by the restoring spring term because $\omega^2 << \frac{c}{m+a}$ [18].
Next, the heave motion of the buoy will drive the unidirectional gear that is installed together with the generator system. This vertical motion is converting into a rotational form that has a speed according to the ratio value of the gear combination used. Also, it is assuming that unidirectional gear will rotate as same as the heaving buoy velocity so that the rotation of unidirectional gear will fluctuate following the time function, as shown in Figure 6. By comparing the use of two wave phases and one wave phase, the results show that the use of two wave phases will produce at least twice the rotational speed compared to one wave phase. Also, if the system is operated in one wave phase only, it will give the result in discontinuous motion (the rotational speed reaches zero value). Of course, this condition is not good because it affects the generated power and increases the friction effect. The utilization of two wave phases in UNOWEC based on a unidirectional system yields an average rotational speed of 44.8 rpm. Besides the continuity of the rotational motion effects by the unidirectional system, the flywheel also gives the continuity by means in the reduction of jam effect in mechanical interaction and keeps the generator rotation in rating range condition. The rotational speed of the unidirectional that affects the flywheel will give the stored energy for the flywheel. This energy can be functioned to increase the power absorption for enhancing the performance of the generator. Hence, the total net captured power of the UNOWEC system ($P_c$) is the product between generator efficiency and the sum of power that captured by the buoy ($P_b$) and flywheel stored power ($P_f$), that expressed as

$$P_c = (P_b + P_f)\eta_g$$

(36)
UNOWEC can only convert some energy from the potentially available sea wave energy with average electrical power is about 1.78 kW and give the absorption ($\eta_b$) is about 17.98%. Nevertheless, oscillating buoy performance is not satisfactory. Since the reference research state that the efficiency range of oscillating buoy is under 20%, this result is acceptable [8] [9].

However, these results need further validation through physical modeling in a wave flume and real sea tests, respectively. The limitation of this study is the assumption of power losses due to mechanical friction of the chain-sprocket system, gearbox, and generator. Therefore, these constraints need further research.

4. Conclusion

Modeling of the UNOWEC with irregular ocean waves has been simulating by the JONSWAP model and numerical computer software. The simulation result shows that the generated data from the assumed spectral density gives well agreements and a good trend. The concept of unidirectional rotation also makes the average distinction about 22 rpm and yields the difference captured power is about 900 W. From the potential wave resource of 12.19 kW/m, UNOWEC can convert this power to about 1.78 kW with a diameter of 1 m. In other words, the absorption of UNOWEC is about 17.98% that appropriate with the reference result. Future work that probably must be done, such as experiments the UNOWEC model in a wave flume; develops a control model to stabilize its output power; and optimizes the mechanical system by considering the friction aspect.

5. Reference

[1] Lisboa, R. C., Teixeira, P. R. F. and Fortes, C. J. (2017) ‘Numerical evaluation of wave energy potential in the south of Brazil’, Energy. Elsevier Ltd, 121, pp. 176–184. https://doi.org/10.1016/j.energy.2017.01.001.

[2] H. Zhang, D. Xu, C. Liu, Y. Wu. Wave energy absorption of a wave farm with an array of buoys and flexible runway, Energy, 109 (2016), pp. 211-223, 10.1016/j.energy.2016.04.107.

[3] Ding, B., Sergienko, N., Meng, F., Cazzolato, B., Hardy, P., Arjomandi, M. (2019). The application of modal analysis to the design of multi-mode point absorber wave energy converters, Ocean Engineering. Elsevier Ltd, 171, pp. 603-618. https://doi.org/10.1016/j.oceeneng.2018.11.058.

[4] Zhao, H., Zhang, H., Bi, R., Xi, R., Xu, D., Shi, Q., Wu, B. (2020). Enhancing efficiency of a point absorber bistable wave energy converter under low wave excitations, Energy. Elsevier Ltd, 212. https://doi.org/10.1016/j.energy.2020.118671.

[5] Hong, Y., Waters, R., Boström, C., Eriksson, M., Engström, J., & Leijon, M. (2014). Review on electrical control strategies for wave energy converting systems. Renewable and Sustainable Energy Reviews, vol. 31, 329–342. https://doi.org/10.1016/j.rser.2013.11.053.

[6] Chen, F., Duan, D., Han, Q., Yang, X. and Zhao, F. (2019) ‘Study on force and wave energy conversion efficiency of buoys in low wave energy density seas’, Energy Conversion and Management. Elsevier Ltd, 182, pp. 191–200. https://doi.org/10.1016/j.enconman.2018.12.074.

[7] Mustapa, M. A., Yaakob, O. B., Ahmed, Y. M., Rheem, C. K., Koh, K. K. and Adnan, F. A. (2017) ‘Wave energy device and breakwater integration: A review’, Renewable and
Shi, H., Huang, S., and Cao, F. (2019). Hydrodynamic performance and power absorption of a multi-frequency buoy wave energy device. Ocean Engineering. Elsevier Ltd, 172, pp. 541–549. https://doi.org/10.1016/j.oceaneng.2018.12.005.

Babarit, A. (2015). A database of capture width ratio of wave energy converters. Renewable Energy. Elsevier Ltd, 80, pp. 610–628. https://doi.org/10.1016/j.renene.2015.02.049.

Rahmati, M.T., and Aggidis G.A. (2016) ‘Numerical and experimental analysis of the power output of a point absorber wave energy converter in irregular waves’, Ocean Engineering. Elsevier Ltd, 111, pp. 483–492. http://dx.doi.org/10.1016/j.oceaneng.2015.11.011.

Shi, H., Liu, Z. and Gao, R. (2012) ‘Numerical investigation on combined Oscillating Body Wave Energy Convertor’, in Program Book - OCEANS 2012 MTS/IEEE Yeosu: The Living Ocean and Coast - Diversity of Resources and Sustainable Activities. doi: 10.1109/OCEANS-Yeosu.2012.6263630.

López, I., Andreu, J., Ceballos, S., Martínez De Alegría, I. and Kortabarria, I. (2013) ‘Review of wave energy technologies and the necessary power-equipment’, Renewable and Sustainable Energy Reviews, pp. 413–434. doi: 10.1016/j.rser.2013.07.009.

Mueller, M. A., & Baker, N. J. (2005). Direct drive electrical power take-off for offshore marine energy converters. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 219(3), 223–234. doi:10.1243/095765005x7574.

Têtu, A. (2017). ‘Power Take-Off Systems for WECs’, in book: Handbook of Ocean Wave Energy. Springer Open, pp 203–220. doi: 10.1007/978-3-319-39889-1_8.

Wang, L. and Isberg, J. Nonlinear Passive Control of a Wave Energy Converter Subject to Constraints in Irregular Waves. Energies 2015, 8, 6528–6542.

McCormick, M. E. (1981). Ocean wave energy conversion. New York: Wiley.

J.M.J. Journée and W.W. Massie.(2001). Offshore Hydromechanics. Delft University of Technology, Delft.

Sheng, W. and Lewis, A. Assessment of Wave Energy Extraction From Seas: Numerical Validation, Journal of Energy Resources Technology, Vol. 134, December 2012.

Morris-Thomas, M. T., Irvin, R. J., and Thiagarajan, K. P.. 2007, "An Investigation Into the Hydrodynamic Efficiency of an Oscillating Water Column," ASME J. Offshore Mech. Arct. Eng., 129, pp. 273-278.

F. Romero, A. Rubio and E. Chica. "Design of a wave energy converter system for the Colombian Pacific Ocean", Revista Facultad de Ingenieria Universidad de Antioquia, no. 94, pp. 8-23, Jan-Mar 2020. [Online]. Available: https://www.doi.org/10.17533/udea.redin.20190406.

Pierson, W. J. and L. Moskowitz (1964), “A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii,” Journal of Geophysical Research, Vol. 69, No. 24, pp. 5181–5190, December.

Sheng, W. and Li, H. A Method for Energy and Resource Assessment of Waves in Finite Water Depths. Energies 2017, 10, 460; doi:10.3390/en10040460.

Longuet-Higgins, M. S. (1962), “On the Statistical Distribution of the Heights of Sea Waves,” Journal of Marine Research, Vol. 11, No. 3, pp. 245–266.

Larsson, K. (2012). Investigation of a wave energy converter with a flywheel and a corresponding generator design. Thesis, Department of Energy and Environment Chalmers University of Technology, Göteborg, Sweden.

Acknowledgment
The authors gratefully acknowledge the financial support from Institut Teknologi Sepuluh Nopember, Surabaya.