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A Novel Rotor Type Wave Energy Converter Design for Maximum Energy Captured in Low Wave Heights

Perihan Karaköse
Ahmet Koca

Bartın University, Bartın Vocational High School, Electronics and Automation, Bartın, Türkiye
Fırat University, Technology Faculty, Mechatronic Engineering, Elazığ, Türkiye

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* Perihan Karaköse&
E-mail address:
perihan.karakose1@gmail.com
Orcid:
0000-0002-8894-6997
* Ahmet Koca
dr.koca.ahmet@gmail.com
Orcid:
0000-0002-0137-6988

ABSTRACT

A wave energy converter system (WEC) is generally used for obtaining electrical energy. Maximize power capture is needed in a range of sea-states. Continuity is improved to control power take-off. But wave energy has a lower force and a higher speed on the costline. Therefore, this paper is investigated the novel rotor type wave energy converter performance in this wave suitable conditional. The performance of this system is tested in laboratory conditions. The aim of the design is maximum power absorption from the low wave height of waves. Results show that the higher wave height has caused the efficiency to decrease in all periods. The highest efficiency is obtained at a minimum wave height of 2 cm. At this wave height, the efficiency has reached its highest value when the period is 5 s (20.3%). In this case, it makes this prototype suitable for seas with low wave height and high wave period.

Düşük Dalga Yüksekliklerinde Maksimum Enerji Yakalamak için Yenilikçi Bir Dalga Enerji Dönüştürücü Tasarımı

Perihan Karaköse
Ahmet Koca

Bartın Üniversitesi Bartın MeslekYüksekokulu, Elektronik ve Otomasyon Bölümü, Bartın, Türkiye
Fırat Üniversitesi Teknoloji Fakültesi, Mekatronik Mühendisliği, Elazığ, Türkiye

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* Perihan Karaköse&
E-mail address:
perihan.karakose1@gmail.com
Orcid:
0000-0002-8894-6997
* Ahmet Koca
dr.koca.ahmet@gmail.com
Orcid:
0000-0002-0137-6988

Özet

Elektrisksel enerji elde etmek için genellikle Dalga Enerji Dönüştürücü sistemler kullanılır. Değişken deniz koşullarında maksimum güç yakalamak gerekmektedir. Güç dönüşüm sistemlerinin kontrolünde ise süreklilik önemlidir. Fakat yakın kıyıda dalga enerjisi düşük kuvvet ve yüksek hıza sahiptir. Bu nedenle bu çalışmada bu koşullar için uygun yeni bir dalga enerji dönüştürücünün performansı incelenmiştir. Bu sistemin performansı laboratuvar koşullarında test edilmiştir. Bu tasarımın amacı düşük yükseklikteki dalgalardan maksimum güç yakalamaktır. Sonuçlarda dalga yüksekliği arttıkça tüm periyotlar için verimin düşmesine neden olmuştur. Maksimum verim 2 cm dalga yüksekliğinde elde edilmiştir. Bu dalga yüksekliğinde verim, 5 s'lik periyotta en yüksek değere (%20.3) ulaşmıştır. Bu durumda, bu prototipin düşük dalga yüksekliği , yüksek dalga periyodu için uygun olduğu söylenebilir.

1. INTRODUCTION

The waves are a powerful and unlimited source of renewable energy. Fluctuation is the oscillation movement of the wind on the water surface. WECs generate energy using this fluctuation. The waves have the potential to cover 20% of the world's energy demands. However, the efficiency of the WEC varies between 10% and 35-40% depending on wind and geographical conditions (Karakose, 2019).

WECs are classified according to the location of the device; coastline, near the coast, and offshore applications. The spread of coastline applications is limited by coastal geology, tidal level, and coastal protection (Clement et. al, 2002)

Near coast type, WEC applications are carried out to depths of water 15-25 m. These systems are usually used to pump the wave energy on shore. WEC system called Oyster is located between near-shore applications. The plate positioned parallel to the sea floor drives the hydraulic pistons by swinging. Electric power is produced by transferring the movement capability to the turbine located on the coast with long pipelines connected to the hydraulic piston (Mert,2012) Near coast type direct-drive WEC studies are not commercialized. In this regard, Youssef (2016) produced 3 W of energy with a small prototype. In the design, two different movements have been obtained for forward and return rotation by using two rack-pinion. Incoming bi-directional motion is passed through the gearbox and transferred to the single wheel. Rotational motion is converted into electrical energy using a generator. Direct drive WEC systems do not provide a high amount of energy in near-shore applications.

Offshore WEC systems are used for high wave regimes in deep waters of more than 40 m. The transmission of energy in these systems only requires long electric cables. Singh et al. (2015) have designed a system of buoys connected to the stick fixed to the ground in offshore applications. 15 kW energy is obtained in this system. Wan et. al. (2017) have developed a design that they call a spar torus, which obtains electrical energy with the combination of wave energy and wind energy. This system, which has a width of 260 m and a width of 10.30 m has designed a prototype by reducing the rate by 1:50. For analysis, regular waves are generated wave height of 2-9 m period 9-23 s. Under these conditions, this system can produce between 100 kilowatt-1 megaWatt. Liu et. al. (2018) have designed an experimental overtopping circular ramp WEC system. A prototype production was reduced by 1:16 for the experimental study. A tank with a dimensions length of 60 m width of 36 m depth of 1.5 m. is used for tests. Water is discharged into the reservoir overcoming the ramp with fins positioned on the circular ramp.

The converters commonly used in the literature work efficiently at high wavelengths. New prototypes continue to be developed to achieve maximum power in all wave profiles. Joe et. al (2014) have designed a robotic system that could benefit from the wave forces maximally for float-type WEC systems. The turbine placed under the float consists of a self-direction low-speed high torque generator. For this purpose, a prototype of 0.3 x 1 x 0.003 m has been used in an area of 3 m^2 and a power of 10.1 W has been obtained. Tom et. al (2016) have conducted a design with variable geometry as an oscillating WEC system. In the design, optimum power output is obtained by matching the hydrodynamic properties of the device according to the frequency change of the wave.

The single-component cannot be optimized separately from the others in WEC systems and WEC components such as wave energy converters, generator movement types, control methods, and power electronics converters of the system have a close relationship with each other. Ozkop and Altas (2017) aimed to define with different perspectives the status of WEC technologies in their review study. Past studies based on WEC systems have been extensively studied and categorized into WEC system components to demonstrate the performance, efficiency, and development of WEC technologies over the past 20 years. They have expressed the usefulness of dividing descriptive parts to provide a better understanding development process of WEC technologies to be able to discuss based on WEC technologies wave energy converters, generators, control methods, controller applied parts, waves, and power electronics types. Therefore, in this study, WEC is explained in parts.

WEC designs are also divided into two according to underwater and floating in the water operation. Sergiienko et. al (2017) compared floating in the water and positioned underwater WEC systems. The power generation of floating WEC systems is higher than those underwater. It is concluded that the power performance of the converters is directly related to the shape of the body and its proximity to the average surface level of the water.

The performance of the designs made in variable waveforms is examined experimentally and numerically. In the literature, there are studies on the closeness of the results of experimental and numerical studies. Ghasemi et. al (2017) have modeled wave energy converters in numerical wave tanks. They use beater and piston-type wave generators. Results are similar in both types of generators. Wavemaker movement, power output amount, and efficiency are calculated model to Columbia Power Technologies product, SeaRay converter at 1:7 ratio by using open source code WEC Simulator (Wec-Sim) (So et. al, 2017). They verify different error rates for different positions, speeds, torque, and power values by comparing models with experimental data. Bhinder et. al (2015) have found the effect of wave energy generation systems on fluid forces using Computational Fluid Dynamics (CFD) analyses. Connectivity to the force effect of the efficiency of the system is examined depending on the time in the fluid environment (Rhinefrank et. al, 2013) Demonstrated a new point absorbing WEC-related numerical analysis and scale wave tank tests are developed by Columbia Power Technologies. Hydrodynamic modeling tools have been used to assess the performance of the WEC. Performance is optimized at full scale and then a 1:33 scale physical model is developed. The physical tests of the 1:33 scale WEC model are carried out in the Oregon State University O.H. multidirectional wave tank. Lejerskog et. al (2015) investigate the effect of buoy size and translator weight on point absorber WEC. Experimental results prove that higher power is produced when the translator weight and buoy size are increased producing electrical energy from oscillation differences in objects by the effect of waves (Dai et. al, 2017). To optimize the geometry and mechanical parameters, the model is tested in the frequency domain and a time-dependent simulation is created to present a numerical hydrodynamic model of a direct drive WEC system (Erikson et. al, 2005). Linear generator is used in modeling to develop numerically direct-drive WEC system by using Reynolds averaged Navier Stokes equations (Chen et. al, 2017). They produce electrical energy by using a liner generator to calculate efficiency for floating buoy WEC (Chandrasekaran et. al, 2019). In their study is used four buoys and is obtained total maximum efficiency of 25% from these buoys to investigate of efficiency of the hemisphere and cylindrical floating buoys in different locations (Chen et. al, 2019). Maximum efficiency is found at approximately 6%. Wahyudie et. al (2018) produce liner hydraulic WEC with a width of 1.2 m, length of 2 m height of 1.2 m, and weight of 600 kg. They obtain output voltage and current values around 241 V and 2.2 A in 0.4 m wave height by using Permanent Magnet Senkron Generator (PMSG). Doe et. al. (2018) stabilization of output power with multi-point absorber WEC. Overall efficiency achieves 27.3% with this prototype-designed hybrid wind-wave energy converter (Perez-Collazo et. al, 2018). Their study used Oscillating Water Column (OWC) WEC. Analysis of OWC performance proves that wave period significantly changes the efficiency of the This device chose typical wave condition for experimental tests in a wave tank with piston type wavemaker (Liu et. al, 2018). They change the water level, wave period, and wave height. Wave height is 50, 75, and 100 mm. Wave period 0.8, 1.0, 1.2 and 1.4 s. In the literature, numerical analyzes have been made for commercialized products and their performance has been evaluated by scaling. WECs suitable for high wave height is also large in size. Examination of experimental data one-to-one numerically takes quite a long time. Therefore, in this study, a prototype that can operate more efficiently at low wave heights has been experimentally tested at a low scale.

This paper investigates the novel rotor-type WEC performance characteristics. Commercialized WECs operate efficiently at high wavelengths. Therefore, in this study, a prototype has been developed that can operate more efficiently at low wave heights. The WEC system of investigated outputs (the applied power, efficiency, current, and voltage value) is recorded for 60 s. The performance of the system is evaluated using the results obtained.

2. MATERIAL AND METHODS

2.1 Wave Forms

This study was carried out in the wave tank of the Fırat University Energy Laboratory.The range of regular wave periods is from 2 to 6 s, wave height is from 2 to 7 cm. The wave tanks are separated from each other by wave makers. The systems that produce a wave in the wave tank are called wave makers. Commonly used models of wave makers are piston, flap, wedge, and snake types. In this work, a flap-type wavemaker is used to provide closer to the actual results. (Karakose,2019) For flap type wave-maker, the wave height-to-stroke ratio is given by Eq.1. Where, T is wave period, $k=2\pi/L$ is wave number, d is water depth, and kd is relative depth (Lee et. al, 2020)

$$\frac{H}{S} = \frac{4(sinhkd)}{kd} \frac{kd \sinh(kd) - \cosh(kd) + 1}{\sinh(2kd) + 2kd} \quad (1)$$

Another main parameter affecting the wave is the ratio of water depth to wavelength. In this formulation, waves are deep translation and shallow waves. In deep water waves, particles move in circles, in shallow water waves particles move on very flat ellipses. Particle movement decreases rapidly (exponentially) with depth in deep water waves but remains essentially the same over the entire water depth in shallow water waves.

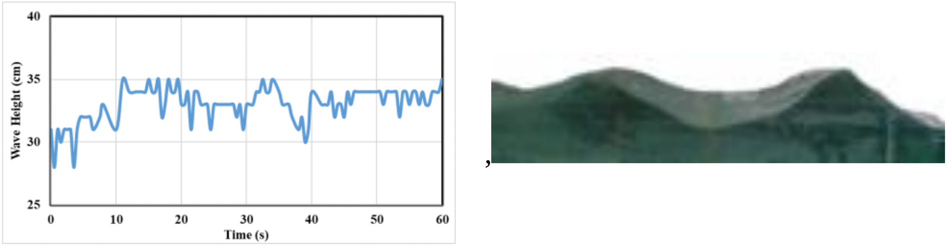
The generated wave model is deep water in the wave tank. In this way, Rapidly changing motion is obtained.

- Deep-water: h/L > 0.25
- Transitional-water: 0.25 > h/L > 0.05
- Shallow-water: 0.05 > h/L

Table 1. Parameters of wave forms

Experiment No	Wave Height (cm)	Wave Period(s)
1	2	3
2	3	3.5
3	3	4.5
4	3	6
5	4	3
6	4	4
7	4	6
8	5	2
9	5	2.5
10	5	5.5
11	6	2
12	6	5
13	7	2

Different types of waves are produced by changing velocity and stroke S. Table 1 summarizes the regular wave test parameters. An ultrasonic distance sensor was used to measure the water level. The ultrasonic distance sensor measures the distance depending on the speed of the sound waves hitting the obstacle. The change in water level was measured by positioning the sensor at the top of the tank. A sound wave is sent in 1 microsecond. The wave heights can be measured up to 7 cm. In this part, measured wave surface levels are given Fig.1. With the effect of the wave, the water splashes around. As a result of the sound waves hitting these splashing waters, the measured values are transmitted with a certain noise. Therefore, Noises are seen at the water level seen in Figure 1. It is observed that this noise increased as the wave height increased.



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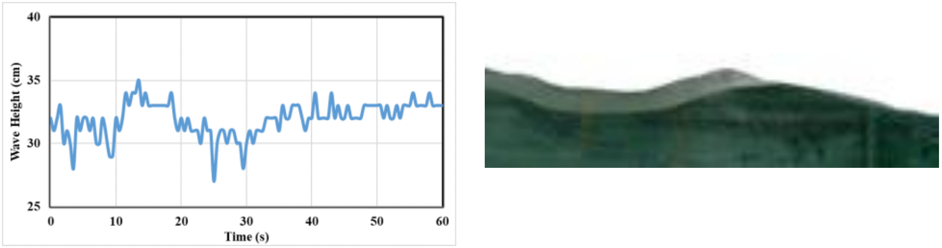

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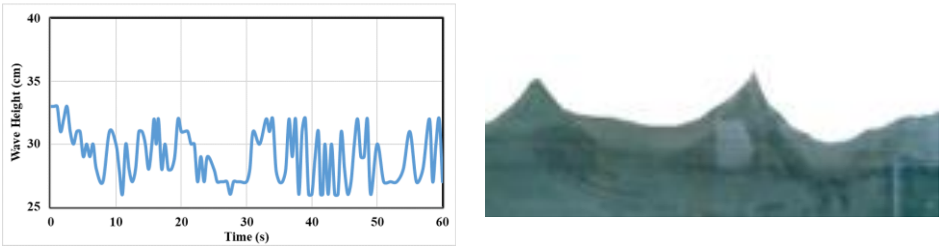


(c)

Figure 1. The wave types were obtained from the wave tank and measured value by water level sensor (a) For wave type 5,(b) For wave type 7 (c) For wave type 13.

2.2. Wave Energy Converter

Wave height and wave period are the main parameters to design a WEC system. Because the power potential of the wave must be the maximum power absorbed by WEC. The wave height of the sea is less that of the ocean. In this study, efficient results are obtained at low wave height. In other words, this system can be appropriated for seas. WEC consists of three parts; body, rotated mass, and PTO system. The body absorbs wave motion. It oscillates with the effect of the wave The center of gravity of the system is sliding due to the oscillating movement. Therefore, the rotating mass moves towards the center of gravity. Representation of Solidworks design WEC is shown fig.2. Dimensions of wave tank is shown fig.3.b and experimental wave tank is given fig.3.a.

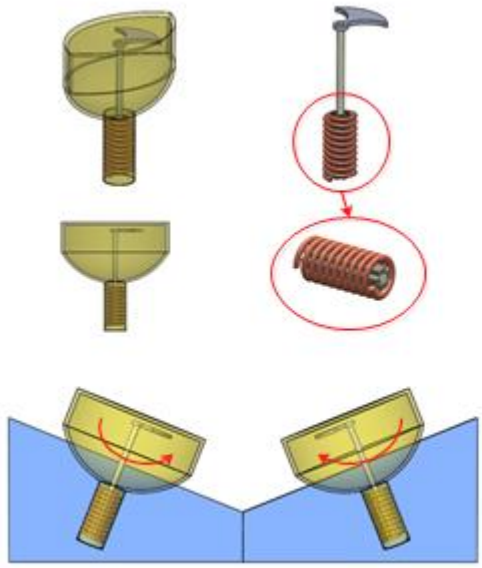
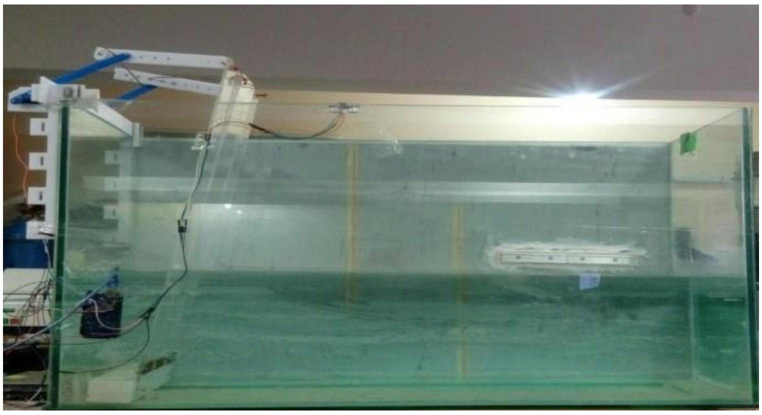
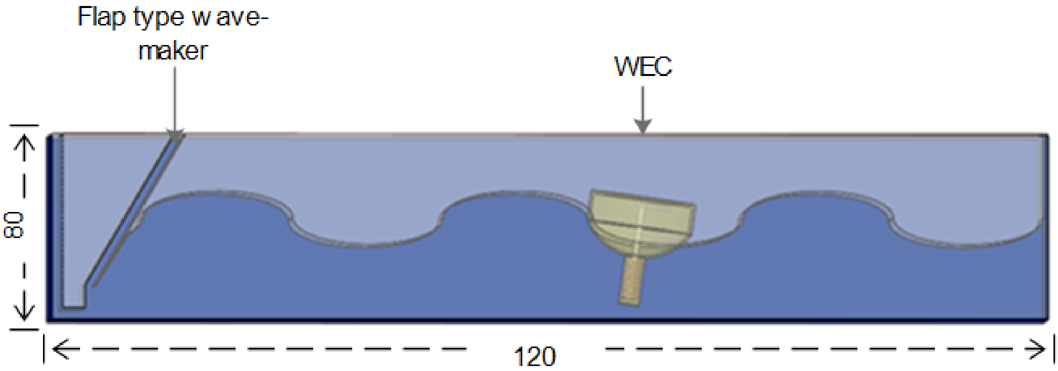


Figure 2. WEC CAD Design



(a)



(b)

Figure 3. Wave tank (a) experimental setup (b) Computer-Aided Design (CAD)

The system is produced by 3D printer technology. Dyo Epoxy Putty Kit is used for waterproofing the WEC. The current passes through the wire by changing the magnetic field inside of WEC. The generator consists of two parts which are a stator and rotor. Magnet is used as a rotor. Produced current and voltage are taken from the coil. Therefore, a magnet is used in the rotor, and a coil is used in the stator to ensure ease of manufacturing. The assembly of WEC is shown in fig.4.

(a) (b)

Figure 4. Experimental WEC (a) without cover (b)with cover

2.3. Power and Efficiency

The wave energy flux per wavelength is found using Eq.2. In the equation, ρ is the density of water and it is taken as 0.99984 g / cm^3 . g is the gravitational acceleration and is taken as 9,80665 m / s^2 . H_m and T are the characteristics of the wave. The power flux of the wave is calculated depending on the different wave heights, and periods (Karakose,2019)

$$P = \frac{\rho g^2}{64\pi} H_m^2 T \; (kW/m) \tag{2}$$

The obtained power from WEC is calculated with Eq.3. In the equation, P_0 gives the amount of power produced as W. Ie value gives the average effective current value,and Ve the value gives the average effective voltage value. cos (φ) gives the phase difference between current and voltage value. The phase angle between current and voltage values is accepted as 0 (Karakose,2019)

$$P_0 = I_e V_e cos\varphi \tag{3}$$

The ratio of the obtained power from WEC to the wave energy flux gives the efficiency of the system. Eq.4 is shown the efficiency of WEC performance.

$$\eta = \frac{P_0}{P}.100 \tag{4}$$

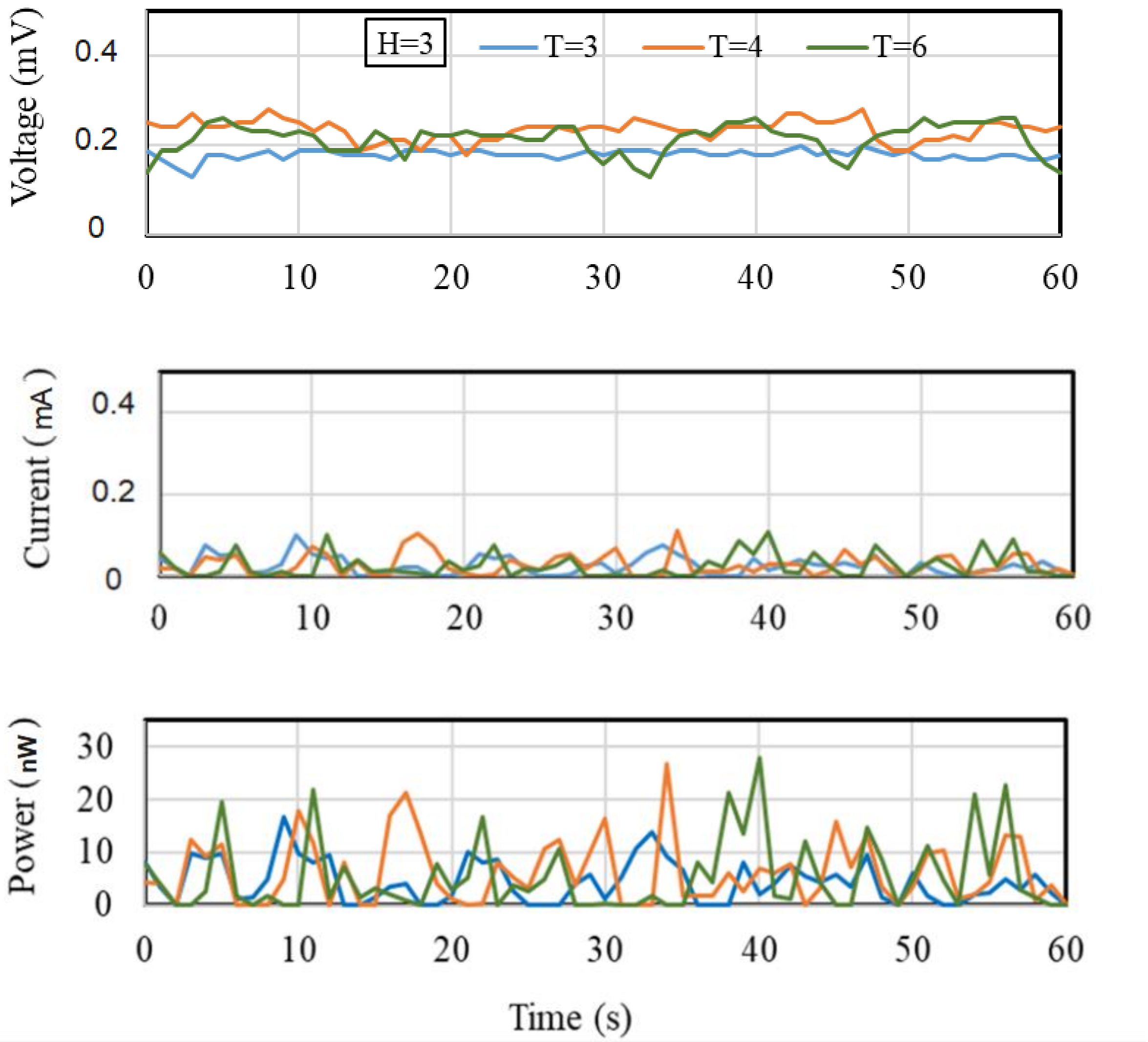
3. RESULTS AND DISCUSSIONS

3.1. Produced Current and Voltage

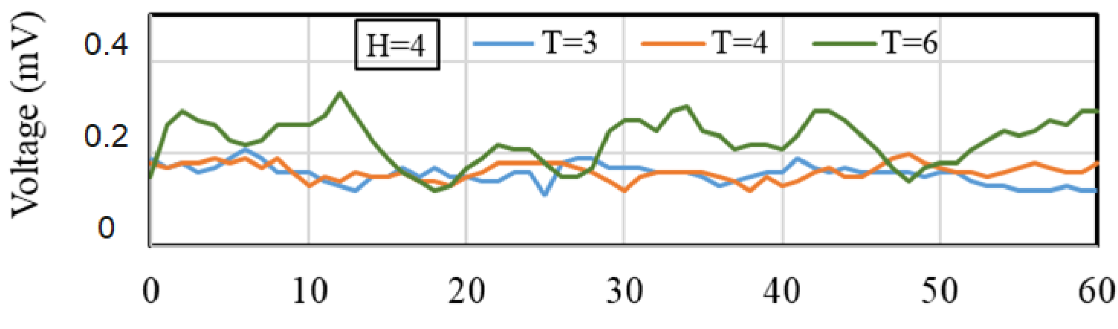
Voltage and current values are taken in 60 s periods for each wave type. Results are shown that the maximum voltage value is obtained for the wave height of 6 cm and wave period of 5 s. The average of the current and voltage values measured for 60 s is given in Table 2. Fig. 5 is shown the values of generated voltage, current, and power. Fluctuation in values of voltage, power, and current are raised when the wave height is 4 cm. The effect of the coil voltage is produced continuously. However, the value produced increases depending on the change in current.

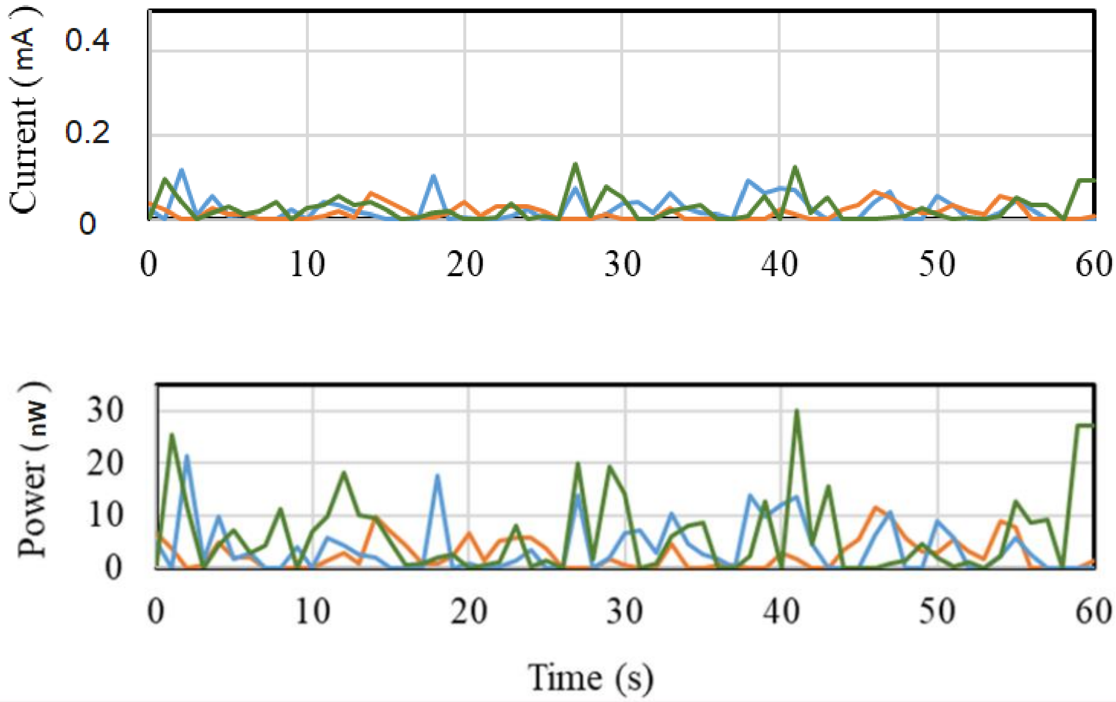
Table 2. Effective current, and voltage value

Wave Form			Effective Voltage Value (mV)	Effective Current Value (mA)	P_0(nW)	P(nW)	η=(P_0/P).100
Wave Type	Wave Height (H)	Wave Period (T)					
1	2	3	0.18	0.02	4.05	44.93	9.01
2	3	3	0.18	0.02	4.43	117.95	3.75
3	3	4	0.23	0.03	6.23	151.65	4.11
4	3	6	0.21	0.02	4.75	202.20	2.35
5	4	3	0.16	0.02	3.61	179.73	2.01
6	4	4	0.16	0.02	2.57	239.64	1.07
7	4	6	0.22	0.02	5.57	359.46	1.55
8	5	2	0.23	0.02	5.29	187.22	2.82
9	5	2.5	0.24	0.03	7.26	234.02	3.10
10	5	5.5	0.23	0.03	6.82	514.86	1.32
11	6	2	0.20	0.02	4.87	269.60	1.80
12	6	5	0.24	0.02	4.88	674.00	0.72
13	7	2	0.19	0.02	3.51	366.96	0.95


Voltage (mV)
H=3
T=3
T=4
T=6
Current (mA)
Power (nW)
Time (s)

(a)


Voltage (mV)
H=4
T=3
T=4
T=6

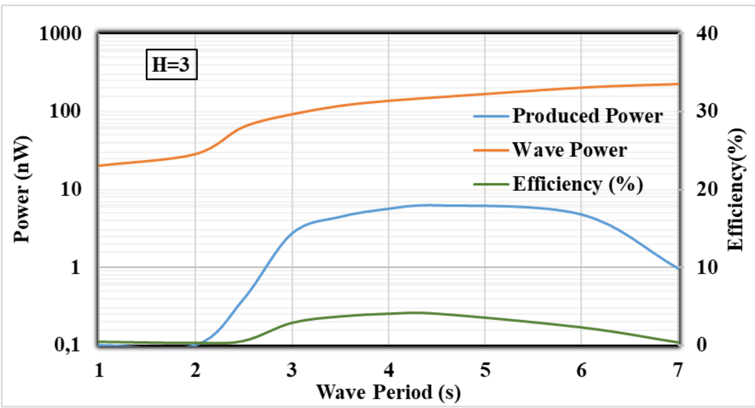


(b)

Figure 5. The voltage, current and power values in stable wave height a) H=3 cm b) H=4 cm

3.2. Generated Power

Power can be generated in every wave period. The increase of the wave period caused the decrease of the generated power for wave height of 4 cm, but it approximately stables for wave height of 5 cm. In this case, the low wave height should be low in the wave period. Because WEC is making more oscillating movements for low wave periods and low wave heights. The purpose of this design is to generate electrical energy using the motion of the wave, not its power. So that the lowest wave height is obtained in a more efficient system. The generated wave power depending on the variable wave period is shown in Fig 6.



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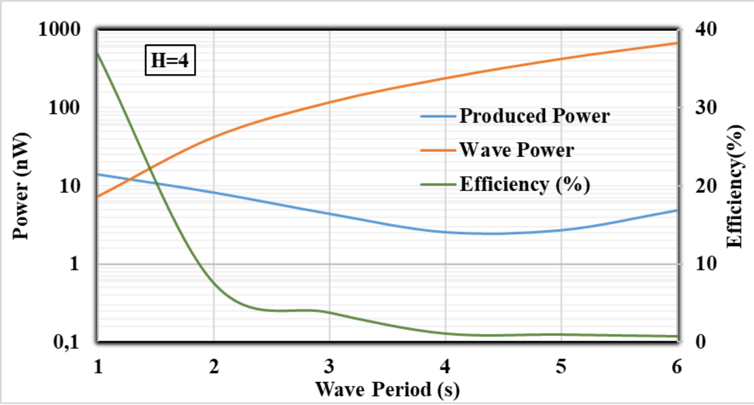

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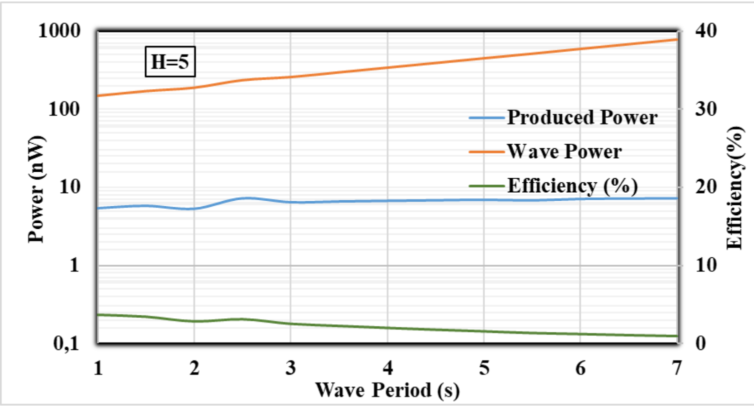
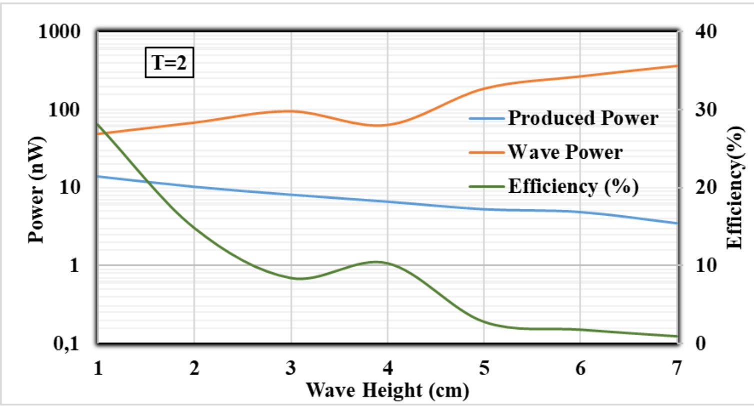


(c)

Figure 6. Power and efficiency charts in stable wave height a)H=3 cm b) H=4 cm c) H=5 cm

The sustainability of generated power is achieved for wave period 2 s. But there are interruptions for wave period 3-5 s. The generated wave power depending on the variable wave height is shown in Fig 7.



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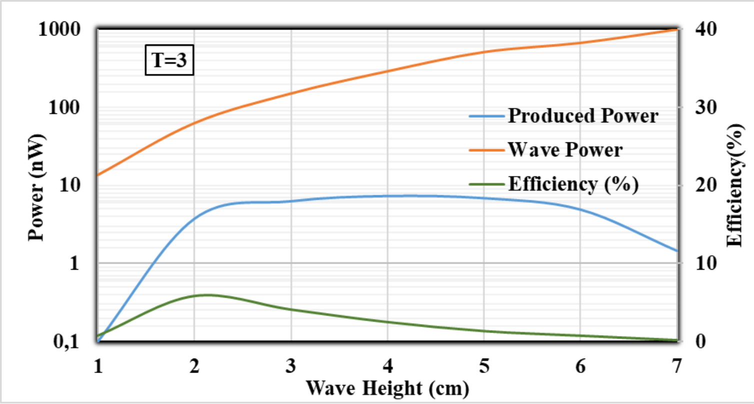

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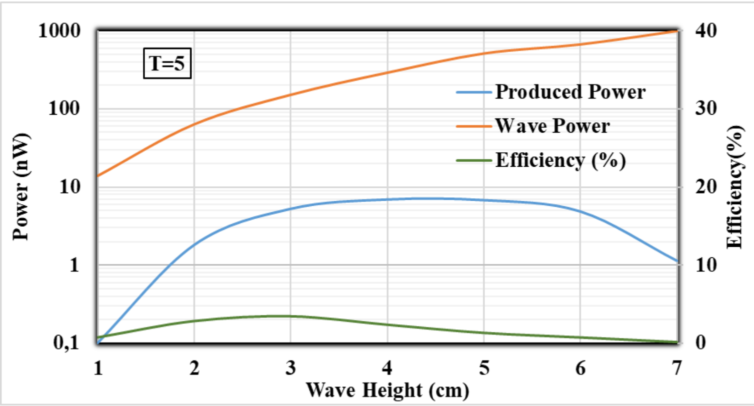
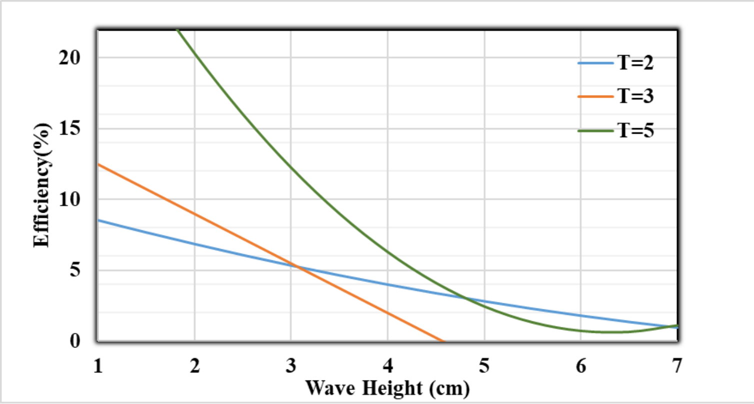


(c)

Figure 7. Power and efficiency in stable wave period a) T=2 s b) T=3 s c) T=5 s

3.3. Efficiency

The efficiency increases depending on the lower wave height. The highest efficiency is observed in the range of 4-5 in lower wave height values (H<5). As wave height increases, efficiency decreases in all periods. The highest efficiency is obtained at 2 cm (minimum wave height). At the same time, the efficiency reached the highest value at 20.3% in the 5 s wave period. Efficiencies vary linearly depending on the period decreases in low wave heights (2-4 cm). In particular, with the higher wave height, in all periods, the efficiency drops below 10%. Fig. 8.a is shown the change of efficiency stable wave height. Fig. 8.b gives the efficiency of WEC depending on the stable wave period.



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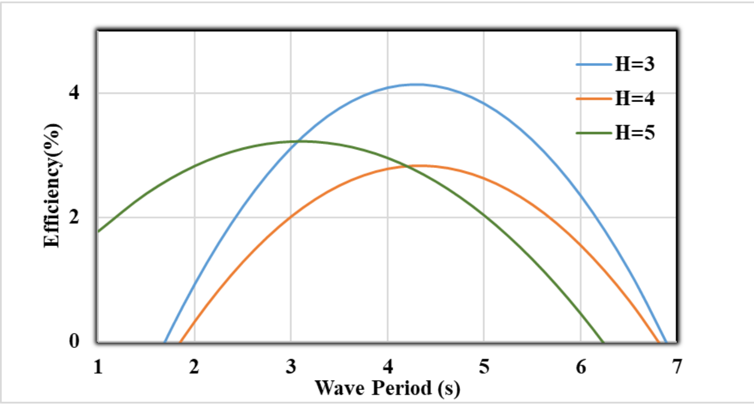

(b)

Figure 8. Efficiency a) The stable wave period b) The stable wave height

Tables 3 and 4 show that the efficiency decreases due to the increase in wave height. This decrease in efficiency is dropped in the lower periods. However, the amount of decrease in efficiency is nominal in the higher periods.

Table 3. Wave power and efficiency change in lower periods

Wave Form		P_0(nW)	$\eta=P_0/P$
Wave Height(H)	Wave Period (T)		
2	3	044.93	9.01
3	4	117.95	3.75
4	3	179.73	2.01
5	2.5	234.02	3.10
5	5.5	514.86	1.32
6	2	269.60	1.80
7	2	366.96	0.95

Table 4. Wave Power And Efficiency Change in Higher Perıods

Wave Form		P_0(nW)	$\eta=P_0/P$
Wave Height (H)	Period (T)		
3	6	202.20	2.35
4	6	359.46	1.55
5	5.5	514.86	1.32
6	5	674.00	0.72

4. CONCLUSIONS

WECs does not efficient in every waveform. Therefore, a unique design is required for each region. The wave height is raised by changing geographic conditions in the seas and oceans. Therefore, seas and oceans have low wave heights for a long time.

When the studies in the literature are examined, their efficiency is low and prototypes suitable for high wave heights have been produced.Therefore, in this study, a prototype that can operate more efficiently at low wave heights, that is, when the period is high, is proposed. A novel rotor-type WEC with directly driving Power Take-off (PTO) is presented experimental conclusion in a wave tank with a flap-type wave maker. The aim of the WEC prototype is maximum power absorption from low waves different conditions of waves are produced in a wave tank and then to capture the oscillating motion created by the wave, an object such as a vessel is used. The oscillating motion is converted to rotational motion by the rotating mass. Finally, this rotational motion is transferred to a shaft surrounded by magnets to generate electrical energy. The main wave parameters are wave height and wave period. The wave heights are set at 2-7 cm and wave periods are set at 2-6 s.

The effects of different wave types on WEC are investigated using the wave tank. Results show that the sustainability of power extraction is achieved in this prototype. Efficiency decreases depending on increased wave height. The highest efficiency (%20.3) is obtained at a minimum wave height (2 cm) and high wave period (5 s). At wave heights above 3 cm, the efficiency drops below 10%. The efficiency approaches each other for higher values. The sustainability of generated power is achieved for wave period 2 s. But there are interruptions for wave period 3-5 s. The rapid increase in the change of water surface achieves an increase in generated power.

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