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Field Study on Oscillating Pontoon Wave Energy Converter (WEC) Performance in Nearby Muarabaru, North Jakarta

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Abstract

With the advancement of technology, ocean wave energy can be converted into valuable electrical energy. This paper aims to determine the performance of a Wave Energy Converter (WEC) device based on a damped forced vibration system. The WEC system consists of a marine structure measuring 3.00 m in height, 2.00 m in width, and 2.00 m in length; a two-dimensional heaving–pitching gearbox used as a Power Take-Off (PTO) system; and an "H"-beam pontoon measuring 2.96 m in length and 0.92 m in width. The study was conducted through field testing along a 50-meter coastal area measured from the low-tide shoreline near Muarabaru, North Jakarta. The testing was carried out for 24 hours, from one high tide period to the next, with observations conducted every 6 hours. The results showed that the output power generated by the heaving motion was 36.25 W, with a heaving efficiency value of $\eta_{heaving} = 25.87\%$. Meanwhile, the output power generated by the pitching motion was 37.9 W, with a pitching efficiency value of $\eta_{pitching} = 27.30\%$.

Keywords: Damped forced vibration system; performance of WEC; pontoon type "H"; power take-off; 2D heaving-pitching gearbox

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1. Introduction

Two-thirds of Indonesia's territory is an ocean area with a number of islands covering more than 13000 islands [1], stretching from west-Sabang to east-Merauke which is almost the same stretch from Los Angeles-California to Raleigh-North Carolina in the United States. It can be can imagined how full of challenges it will be to build an electricity network that crosses the seas between the islands of Indonesia. A challenge that requires thinking and solving to overcome the power grid. Not only does function for lighting, but electricity also plays an important role and is very much needed for people's daily activities, both by urban and rural communities as well as by the industrial world, Micro, Small, and Medium Enterprises (MSMEs) or Small and Medium Enterprises (SMEs) for example; for the world of education and so on; for coastal fishing communities, they can use refrigeration equipment to preserve their catch that can be sold to various cities with higher economic value. Even the Indonesian government launched the Program Indonesia Terang (PIT), which targets 12,695 villages in six provinces in eastern Indonesia and only focuses on new and renewable energy such as micro-hydro, wind, and solar.

Indonesia, as an archipelagic country with thousands of islands reaching more than 13,000 islands, has varying wave heights based on its geographical position, wave heights ranging from 0.5 to 2.5 m in the Indian Ocean covering the waters south of Java to the west of West Sumatra for example [2], and has great potential to be considered and developed into a source of renewable energy, green and environmentally friendly energy, and a substitute for fossil energy.

In the western season, significant wave height in the waters of Pelabuhan Ratu, ranging from 0.45 – 1.55 meters. Meanwhile, in the east monsoon, the significant wave heights are relatively the same, namely 0.4 – 1.58 meters; seasonal factors have no effect on significant wave height characteristics in the waters of Pelabuhan Ratu [3]. N(national), P(policy), E(energy) mandates a target of the renewable energy mix in the primary energy mix of at least 23% by 2025 and minimizing the use of petroleum to less than 25% by 2025. In addition, energy efficiency is also targeted to decrease by 1 % per year to encourage savings in energy use in all sectors [4]. So the only way to reduce fossil energy is only renewable energy including wind, ocean wave energy, geothermal, hydro, and solar which provide a clean energy source environment free of carbon dioxide [5], [6]. The force per unit width that can be absorbed from the mechanical energy of waves coming from the front or bow in naval architect terms is proportional to the square of the amplitude and period of motion and the behavior of sea waves is that with the seabed getting shallower towards the coast, the wave height will be higher, otherwise, the wavelength will be shorter [7]. Review of the theoretical formulation and

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challenges in the future development of energy converter technology and its analysis that the potential for sea wave energy for alternative energy is very large but cannot be utilized optimally because the development of wave energy converter technology is still on a prototype scale, as well as the statement that the impact of using wave converters sea to the environment is not significant compared to conventional energy [8]. In general, the wave energy mechanical converter (MWEC) machines used today can be grouped into 3 (three) groups, Fig. 1, namely:

1. Converter oscillation buoy (OBC),
2. Converter overtopping (OTC),
3. Water column oscillation converter (OWC)

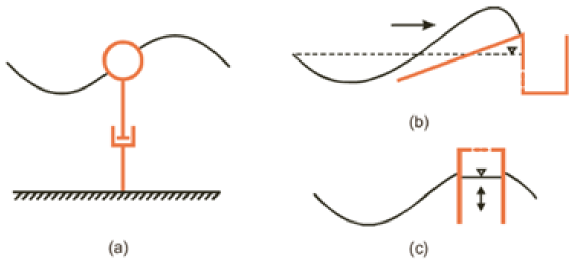

Figure 1. Classification of wave energy devices. (a) converter oscillation buoy, (b) converter overtopping; (c) water column oscillation converter [9-10]

Although the wave energy technology known as the wave energy converter (MWEC) device is still relatively new compared to wind and solar technology, for example, several researchers have started research and proposed a new design for MWEC technology [11]–[14]. Optimization of each electro-mechanical drive component can be improved by increasing the speed ratio of the gearbox with the assistance of Simulink and Matlab modeling software or by selecting generator ratings according to sea conditions and motion profiles [11]. An analytical model was developed to describe the interaction of a one-way gear wave energy converter utilizing the gravitational force of gravity with irregular ocean waves using the JONSWAP (Joint North Sea Wave Project) model. The numerically simulated model shows that wave height greatly determines the converted output power [12]. A new compact mechanical PTO using a ball screw mechanism and Mechanical Movement Rectifier (MMR) to improve energy conversion performance has been introduced where their experimental results show that compared to the traditional linear PTO which uses a ball screw to drive the generator directly, the MMR PTO is more efficient due to its unique freewheeling motion, achieving a maximum energy transfer efficiency of 81.2%, and testing in a water tank yields a total PTO efficiency of up to 62.4%, indicating a very promising potential for real applications [13]. Linear–sliding WEC placed on buoy buoys and constructed into a single unit has been made and tested at sea in swell and random conditions. For the 3 m long LS-WEC with a translator mass of 30 kg it floats on the sea surface with a nominal wave height of 1.25 m and a wave period of 5 seconds, the results show an efficiency of 85 percent and the magnitude of the power is proportional to the height of the wave [14]. A design optimization study for a Power Buoy (WEC) wave energy converter using WEC-Sim software and comparing four variations of the Power Buoy design in extreme sea conditions and directional waves, assuming a wave environment of Humboldt Bay, California has been studied whose results are expected to be a development framework WEC design in future projects [15]. Harvesting wave energy is a clean, emission-free way and environmentally friendly procedure compared to conventional energy conversion technology. Also, a discussion about declutch control, reactive control, model prediction control, etc. for the three main types of wave energy converters (OWEC), i.e. oscillating body wave energy converter (including point absorber, attenuator, and terminator), the water column oscillates and device overtopping has been discussed [16].

In this study, a new prototype was designed and proposed for a wave energy converter (WEC) device, namely the H beam type pontoon oscillating WEC device as shown in Fig. 2 with its 2D gearbox as shown in Fig. 3. The real sea trials were carried out on the coast (shallow waters) of nearby Muarabaru, North Jakarta.

Figure 2. H-Beam type wave energy converter (WEC)

Figure 3. Two-dimensional gearbox

2. Material and Method

2.1. *Wave energy converter machine*

The way this wave energy converter machine tool works is first of all, the wave energy provides energy to the pontoon which causes heaving and pitching motions on the H-type pontoon, which results in an elongation of the spring installed in the gearbox. The mechanical energy of the spring then transfers its energy to the damped forced vibration system and finally produces the power take-off of the wave energy converter machine device.

2.2. *Mechanical energy of waves*

Ocean waves carry and transfer mechanical energy to the pontoon as input from the pontoon oscillating engine power with large power (W) assuming that the wavefront is related to the lambda wavelength, and the wave height H and width b, can be obtained from [7].

$$P_w = \frac{1}{16}\rho g H_s^2 T_s \tag{1}$$

or written in energy units (Joule) is

$$P_w = \frac{1}{16}\rho g H_s^2 \tag{2}$$

where P_w is the wave power per unit horizontal area (W/m^2), ρ is the specific gravity of water, g is the acceleration due to gravity, T_s is the wave period and H_s is significant wave height.

2.3. Spring mechanical energy

Due to the constant spring on the pulley of the gearbox, the mechanical energy generated by the pontoon which is also the mechanical output of the OPC WEC can be written as follows:

$$EM = \frac{1}{2}kx^2 \tag{3}$$

2.4. Damped forced vibration

The schematic of the damped forced vibration system used in analyzing the performance of the wave energy converter (WEC) machine device can be seen in Fig. 4.

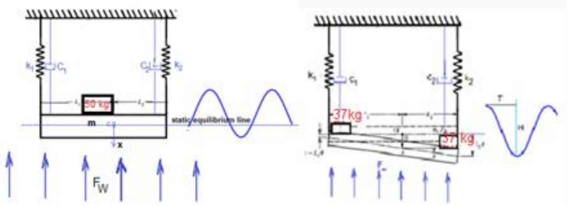

Figure 4. Representation of a simple heaving and pitching motion of the WEC device

If the angle of rotation is considered small, then the equation of motion at coordinates $x(t)$ and $\theta(t)$ are:

$$ma = \Sigma(forces)$$

$$m\ddot{x} = -c_1\dot{x} - c_2\dot{x} - k_1x - k_2x + F_w(t) \tag{4}$$

From [10] namely

$F_{pto} = -c_1\dot{x} - c_2\dot{x} - k_1x - k_2x$, then the eq. (4) reduces to:

$$m\ddot{x} = -F_{pto} + F_w(t) \tag{5}$$

and

$$J\ddot{\theta} = \Sigma(moments)$$

$$J\ddot{\theta} = -c_1(\dot{\theta})L_1 - c_2(\dot{\theta})L_2 - k_{t1}(x - L_1\theta)L_1 - k_{t2}(x + L_2\theta)L_2 + M_P(t) \tag{6}$$

and the same way as Eq. (4), namely

$$M_{pto} = -c_1(\dot{\theta})L_1 - c_2(\dot{\theta})L_2 - k_{t1}(x - L_1\theta)L_1 - k_{t2}(x + L_2\theta)L_2$$

then the Eq. (6) can be reduced to:

$$J\ddot{\theta} = -M_{pto} + M_P(t) \tag{7}$$

The equations of motion (4) and (6) are called the heaving equation of motion and the pitching equation of motion, respectively.

2.5. Model of H beam type pontoon

The pontoon model shown in Fig. 5, is made of an arrangement of four drums sized as shown in Table 1.

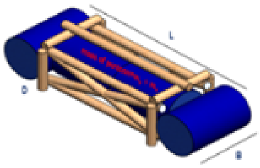

Figure 5. Pontoon type "H" beam

Table 1. Design parameters of the H beam type pontoon

Item	Diameter (m)	Length (m)	Material
Drum	0.56	0.92	Plastic
Ponton (4 drums)	0.56	2.86	Plastic

2.6. Measuring instrument

The Lutron brand digital anemometer with a range of 0.80–30 m/s model AM-4200, as well as the digital torque model TQ-8800 are used to monitor wind speed and torque to the turbine shaft; Sanwa analog multitester model YX360TRF for determining volts and amps; TaffSTUDIO LCD Digital Laser Photo Tachometer 2.5-100000 RPM - DT-2234C+ - Black; and a 12 volt DC generator as shown in Fig. 6.

Anemometer Torsimeter

Multitester Tachometer Generator

Figure 6. An apparatus consists of a digital anemometer, tachometer, digital torque, multitester, and a generator

2.7. Experimentation

2.7.1. Undamped free vibration test

At first, the gearbox chain was given a load of 30 kg (300 N) and the elongation value was measured as delta = 27.22 cm, and the spring constant k= 1102.1 N/mm was obtained. The spring constant test was repeated for the same spring but with a different load of 370 N, an elongation value of 35.22 cm was obtained, and a spring constant k = 1041.7 N/m, as shown in Table 2.

Table 2. Experiment results of undamped free vibration test

Item	Weight (N)	Ellongation (m)	Spring constant k (N/mm)
Spring for heaving	300	0.2722	1080.1
Spring for pitching	370	0.3522	1029.5

2.7.2. Dumped forced vibration experiments in the open ocean

Initially, the pontoon in an empty condition was floated into the open sea and given a mass load of 30 kg in the middle. Then, through the heaving gear, the chain attached to the heaving spring is connected to the center of the pontoon where the 30 kg mass is located. The voltmeter and ammeter are then connected in series and parallel with a damped forced vibration gearbox as a power source. Wind speed and sea temperature are monitored and anemometers and temperature sensors are activated to monitor weather conditions. Various wave heights are applied between 0.10 meters to 1.0 meters on the pontoon, readings on the multi tester, along with the corresponding instantaneous values for voltage, current, and PTO power take-off shaft speed in revolutions per minute (RPM) as measured by the tachometer for each wave height value. The gearbox torque as PTO output is also measured with a torque meter gauge aligned and linked to the wave height; Measurements were made 4 times every six hours according to the tidal cycle for 24 hours. These values are recorded in hand notes in tabular form. Then it is analyzed from the tabulation results, to calculate the power and torque of the WEC device. This procedure was repeated for the condition of a mass load of 37 kg which was located at each end of the bow and stern for the pitching motion experiment, namely by connecting the gearbox chain after passing the pitching gear to the pitching spring and to each end of the bow and stern of the pontoon where the mass load was 37 kg.

WEC device performance assessment can be assessed from measured parameters such as the resulting power value which is expressed as follows:

$$P = V \times I \; [Watts] \qquad (8)$$

where the voltage V (Volt) and current I (A) are obtained from the experimental results. Then the performance of the WEC device as a nondimensional parameter is obtained as follows:

$$\eta_{WEC} = \frac{Power\ Out}{Power\ In} = \frac{P,Eq(8)}{P_w,Eq(1)} \times 100\% \qquad (9)$$

as well as the performance of torque as a non-dimensional parameter which can be expressed as follows:

$$\eta_T = \frac{Torque\ Out}{Torque\ In} \times 100\% \qquad (10)$$

where the torque out T (N.m) and shaft rotation out N (rpm) are obtained from the experimental results.

3. Results and Discussion

The results of experimental studies and theoretical calculations, the authors tabulate in Tables 3 to 4 which are then described in graphical form as shown in Figs. 7 to 9.

Table 3. Field test results due to heaving motion

H (m)	Lambda (m)	V (Volt)	I (mA)	Pexp (watts)	N (rpm) Heaving	T (N.m)
0.14	0.60	17.2	586	10.1	44.5	1.8
0.15	0.70	18.4	928	17.1	58.3	2.7
0.16	0.80	19.7	1298	25.5	73.2	3.6
0.17	0.90	20.6	1638	33.7	83.9	4.4
0.18	1.00	21.4	1873	40.2	91.5	5.0
0.19	1.10	22	2022	44.3	97.0	5.5

Table 4. Field test results due to pitching motion

H (m)	Lambda (m)	V (Volt)	I (mA)	Pexp (watts)	N (rpm) Heaving	T (N.m)
0.14	0.60	18.0	618	11.1	67.6	2.9
0.15	0.70	19.3	983	19.0	79.7	4.2
0.16	0.80	20.7	1335	27.6	93.2	5.3
0.17	0.90	22.0	1688	37	105.3	6.2
0.18	1.00	23.0	1890	43.3	113.5	7.1
0.19	1.10	23.7	2018	47.8	119.0	7.8

Notation for Table 3 and Table 4: *H* is the wave height, lambda is the wavelength, *V* is the voltage, *I* is the current, *Pexp* is the result from the experiment, namely the voltage multiplied by the current, *N* is the gearbox shaft rotation and *T* is the torque.

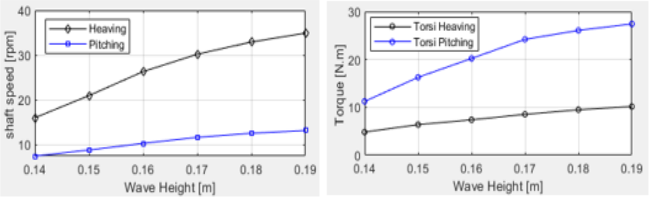

Figure 7. Shaft rotation and torque value curves of the WEC device

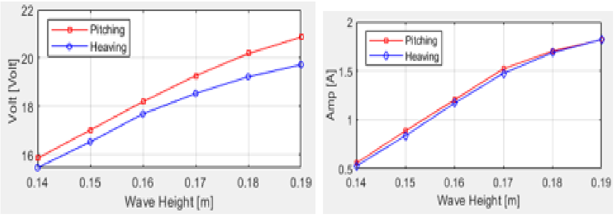

Figure 8. Voltage and current curves of the WEC device

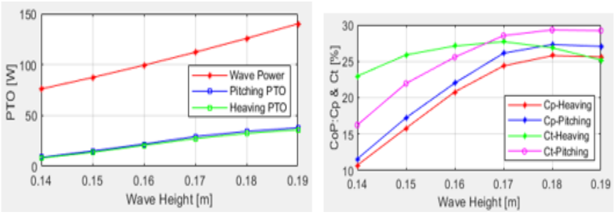

Figure 9. Power take-off and efficiency curves of the WEC device

4. Analysis

To the statement of the research objective, namely to investigate and verify the performance of the Wave Energy Converter (WEC) device, at variations in wave height between wave heights of 0.14 meters to 0.19 meters, the experimental results from the WEC prototype oscillating heaving pitching pontoon type H beam can be seen in Figs. 7 to 9. In general, the experimental results show that this type of WEC device operates at sea wave height values in the nearby Muarabaru coast of North Jakarta, namely operating at low wave heights, including the Java Sea which has an average wave height of 0.25 m [2].

From Fig. 4, it shows that the relative vertical displacement of the heaving motion is assumed to be x, on the other hand, the relative vertical displacement of the pitching motion is $x+1/2\ L+\theta$, which means that:

$$x + \frac{1}{2}L + \theta > x$$

where L is the length of the ponton hull and θ is pitching angle.

Or it can be said as shown in the equation of motion of Eqs. (4) and (6) that the spring elongation given to the heaving spring is smaller than the spring elongation given to the pitching spring so that the power obtained in the pitching motion will be greater than the power obtained in the heaving motion, Fig. 9.

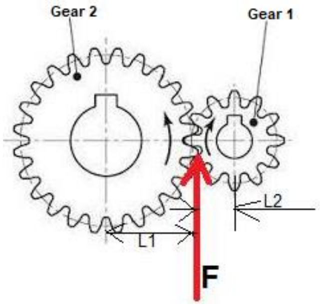

Figure 10. Gear train system

It can be seen in Fig. 10 that gear no.2 (driving gear) has 35 teeth while gear no. 1 (driven gear) has 22 teeth, so it can be ascertained that:

$$L2 > L1$$

Since the force F applied to the driving gear for the heaving motion is 300 N, while the force applied to the driving gear for the pitching motion is 370 N, then it is clear that the torque value produced by the pitching motion will be greater than that produced by the heaving motion, but on the contrary, its rotation is lesser than that produced by the heaving motion as shown in Figs. 7 and 8.

5. Conclusion

The H-beam type pontoon oscillating WEC device is a promising concept for small and medium-scale ocean wave energy systems, with a WEC generated power due to heaving of 36.25 Watts with an efficiency of \eta_{heave} =0.26%; while the power generated by WEC due to pitching is 37.9 Watts with an efficiency of \eta_{pitch} =0.27% at wave heights between 0.14 meters to 0.19 meters. Therefore, one of the objectives of this field test over the open ocean is to identify optimal WEC device performance which will lead to higher efficiency values. In conclusion, the authors can say that with a few further modifications, namely by extending and widening the dimensions of the H beam pontoon type and increasing the number of springs on the gearbox as well as the mass load applied to the pontoon hull, for example, the H beam pontoon oscillating type WEC device system can be said to be suitable for small and medium-scale wave energy conversion in areas with sea wave height conditions that are by the realistic geographical conditions of Indonesia.

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