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Modelling of One Way Gears Wave Energy Converter for Irregular Ocean Waves to Generate Electricity

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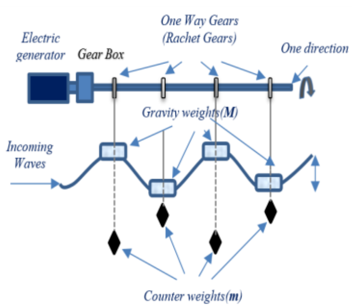
Masjono[a*], Salama Manjang[b], Dadang A. Suriamiharja[c], M. Arsyad Thaha[a]

[a]Department of Civil Engineering, Hasanuddin University, Makassar, Indonesia
[b]Department of Electrical Engineering, Hasanuddin University, Makassar, Indonesia
[c]Department of Physics, Hasanuddin University, Makassar, Indonesia

*Corresponding author
masjono@kemenperin.go.id

Graphical abstract



Abstract

The prediction of converted energy by one way gears wave energy converter may be influenced by non-linearity properties of the ocean waves. To date there has not been an adequate analytical model to predict the power production of one way gear wave energy converter under irregular wave condition. In this work, analytical model is developed to describe the interaction of one way gear wave energy converter that utilized gravity force of the gravityweight (M) with irregular ocean waves using JONSWAP (Joint North Sea Wave Project) model. This interaction model has been simulated numerically by means of computer software. The simulation result showed that wave height is strongly determining the converted output power. The outcome of harnessing the gravity force instead of buoyant force of this proposed model that commonly used by the previous wave energy converter demonstrate significant potential output power. The proposed model can be used to design feasible and efficient wave energy converter.

Keywords: Renewable energy; wave energy converter; irregular ocean waves.

1.0 INTRODUCTION

The global economy is growing exponentially, the whole world spend large sum of investment which trigger the high consumption of energy resources to gain maximum profit. As the earth resources become increasingly scare, countries around the world are entering the era of environmental protection and energy conservation. Reduction of carbon emission needs to be controlled. International Agency reported that the Global emissions of carbon dioxide stood at 32.3 billion tones in 2014, unchanged from the preceding year [1].

United Nations goal on energy sector by 2030 has three main objectives; to ensure universal access to modern energy services, to double the global rate of improvement in energy efficiency, and to double the share of renewable energy in the global energy mix. [1]. Recent world energy survey conducted by world energy council in 2013 reported that by 2020, fossil energy (coal, natural gases and oil) still dominated the world energy consumption which contribute about 76 %, followed by renewable energy 16 %, Nuclear 6 % and hydropower greater than 10 MW 2 % respectively [2].

An ocean wave is a potential source of renewable energy that has not widely harnessed until the oil embargo in 1973-1974 by Arab countries [3]. This energy sources is available 24 hour a day and posse's power density 832 times higher than the wind flowing to drive a wind turbine [4]. Wave energy converter technology is dated back to 1799 when the first converter was patented in Paris by Girard and his son. In 1910 Bochaux-Praceque contracted wave device to light and power his house at Royan near Bordeaux in France. He introduced the first oscillating water column type of wave energy converter device [5].

The source of the ocean wave is initiated where wind and water interact in the open ocean and travel with small energy loss until nearing the shore. Its energy is lost through friction against the sea floor and breaking on the shore. This is known as the cycle of the wave. Ocean wave parameters are classified by height, wavelength and wave period. The crest is the highest part of the wave, while the trough is the lowest part. The height is the vertical distance from the crest to the trough [6]. These parameters varies depends on wind speed fetch length and sea floor depth. Therefore, these parameters also impose changes in Wave Energy Converter (WEC) outputs. When the WEC runs at wave conditions below what it is designed for, it is called part-load operation. Similarly, wave conditions exceeding design conditions impose overload operation. At these two operating conditions, WEC output is reduced (i.e., the energy conversion efficiency drops). The overload could also lead to significant structural damage. Thus, load variation is unavoidable in WECs, and the variations can be inherent to the cycle of the wave itself or could be imposed as a result of external conditions, such as weather profile, bathymetry and surface friction [7].

Wave energy is the transport of power by ocean surface waves, and it has high availability, density and good predictability compared to other renewable energy sources. A number of work for converting wave energy to electricity have been developed in the past decades [8]. This paper focus on a wave energy converter concept developed at Water Resources Engineering Laboratory, Department of Civil Engineering, Hasanuddin University, Indonesia. The WEC contain five main parts, a gravity weight, counter weight, rotating shaft, ratchet gear and electric generator [9].

Early studies shows that the irregularity properties of ocean wave was not taken into account, therefore, its output power prediction only valid for regular waves. In order to evaluate the performance of this WEC in real seas, the analysis of the WEC under irregular waves is necessary [8]. Some theoretical and experimental studies to cope the irregular wave's effect on WEC have been investigated. This paper proposed a modified model of one way gear wave energy converter to cope the variation of ocean wave's properties.

2.0 METHODOLOGY

2.1 Wave Model

In order to evaluate the performance of the WEC in real seas condition, it is necessary to analyze the WEC under irregular waves. For waves generated by wind, it can be described by means of superposition theory which assumes that the wave heights are small compared to the wave length. Then the irregular ocean waves is the sum of a number of regular waves with different amplitude and frequency, therefore irregular waves can be created by summing regular wave component of small amplitude, random phase and different frequency [10] [8].

$$Y_t = \sum_{i=1}^{N} A_i Cos(\omega_i t + \theta_i) \quad (1)$$

Where Y_t, $\omega_i = i \, x \, \omega_0$, θ_i, A_i are the elevation of water level at time t, angular frequency, phase, amplitude of the i^{th}harmonic wave respectively. ω_0 Is the fundamental angular frequency derivedfrom:

$$\omega_0 = \frac{\omega_{max}}{N} \quad (2)$$

Where $\omega_{max}$the maximum frequency componen is that present in the wave spectrum and N is the number of wave components.

The common measure of wave power, P, is [11]

$$P = \frac{\rho g^2 T H^2}{32\pi} \quad (3)$$

Watt per meter (W/m) of crest length (distance along an individual crest),

Where:

ρ = the density of seawater = 1,025 kg/m^3,

g = acceleration due to gravity = 9.8 m/s,

T = period of wave (s), and

H = wave height (m).

2.2 Waves and Gravity Weight Interaction

The gravity weight use in this proposed WEC is a container filled with less than 80% sea water to keep it floating on water surface. See Figure 1. The amount of converted energy from ocean wave oscillation is determined by the mass of counter weight. Light weight container materials filled with sea water can be used. Dense or heavy material is used for counter weight. Illustration on Figure 1 shows that there are two forces acting on gravity and counter weights heave or vertical motion; gravity force and buoyant force respectively. The gravity weight is floating on water surface and the counter weight is sink to pull down the rope when the gravity weight moving upward.

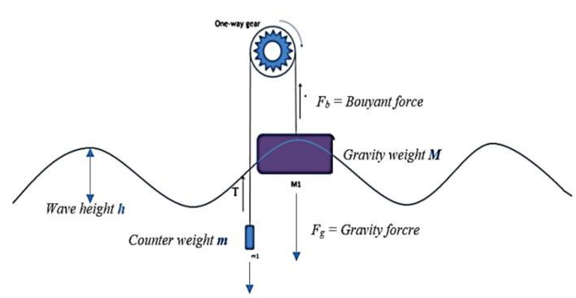


Figure 1 Interaction between converter and regular ocean waves

Gravity force or potential energy[12] :

$$F_g = MgH \quad (4)$$

Where F_g, M, g and H are gravity force, gravity acceleration, wave height peak to through respectively.
Buoyant force[13]:

$$F_b = \rho g V \quad (5)$$

Where F_b, ρ, g and V are sea water density, gravity acceleration, and volume of water displace by the gravity weight (M).
Similarly, Forces described by equation (3) and (4) are acting on counter weight as well. Therefore, the difference between forces acting on gravity and counter weights are equal to the amount of extracted energy from this converter.
Energy contribution of each pair of gravity weight connected to counter weight by mooring line through one way gears to drive the rotating shaft is formulated as follows;

$$P = (M - m)g\, Y(t)\ Watt \quad (6)$$

Where P, M, m, g, H and $Y(t)$ are potential energy, gravity weight mass, counter weight mass, gravity acceleration(9.8 m/s), wave height and irregular wave function respectively. Hence, substitution of equation (1) into equation (6) yield the extracted power by one pair of gravity weight for irregular waves is expressed in equation (7);

$$P = (M - m)g \sum_{i=1}^{N} A_i Cos(\omega_i t - \theta_i)\frac{dy}{dt} \quad (7)$$

$$P = (M - m)g \sum_{i=1}^{N} ||A_i \omega_i Sin(\omega_i t - \theta_i)|| \quad (8)$$

2.3 Power Take Off (PTO) System

The Proposed wave energy converter block diagram is described in Figure 2. The conversion process started from the interaction of the incoming wave with gravity weight. This interaction will transfer the energy flux in ocean wave into gravity weight to move in vertical motion (heave). This movement is connected to ratchet gears (one way gears) and counter weight. The heave movement of gravity weight will cause the shaft to rotate in one direction. A series pairs of ratchet gears are connected in common shaft create shaft continuous rotation in one direction[9].
The interaction of each gravity weight with ocean waves contributes equal amount of potential energy at the different phase to drive the rotating shaft which is coupled with generator. In case of regular waves, the contribution of each pairs of gravity weight is illustrated in Figure 4. However, any floating structure at sea will be subjected to irregular sea states which makes analyses of irregular sea states are important.

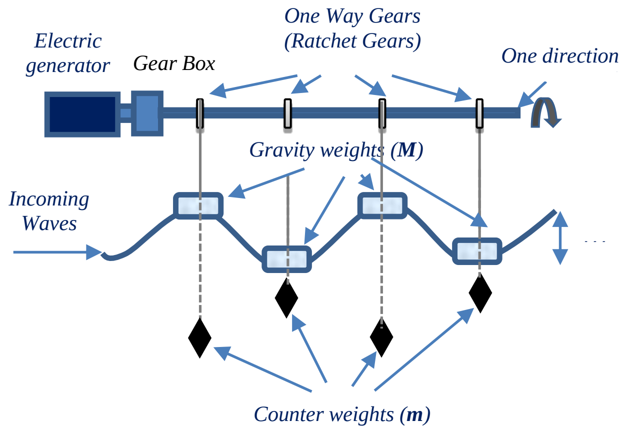


Figure 2 Illustration of WEC Concept developed at Water Resources Engineering Lab, Dept. of Civil Engineering, Hasanuddin University, Indonesia.

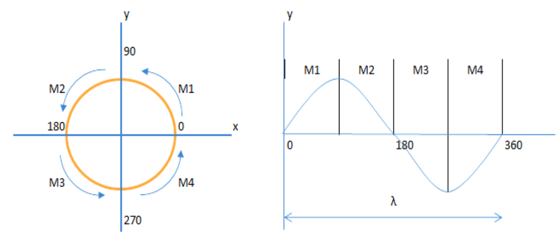


Figure 3 Illustration of four gravity weight to convert oscillation of linear ocean wave into one direction shaft rotation [9].

Harnessed Power take off (PTO) from irregular waves by a series of one way gears converter as illustrated in Figure 2 can be calculated using equation (7) by multiplying this equation with the number of gravity weights pairs. For example, if converter use four pairs of gravity weights as illustrated in Figure 2, then simply multiply equation (7) with the number of gravity weight pairs.

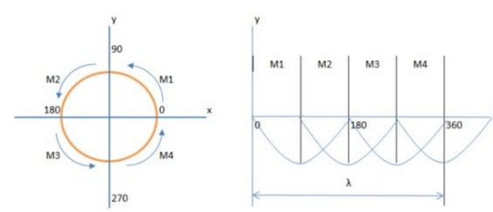


Figure 4 Graphical representation of energy received by rotating shaft converted by four gravity weights [9]

$$P = 4(M - m)g \sum_{i=1}^{N} ||A_i \omega_i Sin(\omega_i t - \theta_i)|| \quad watt \quad (9)$$

Or

$$P = n(M - m)g \sum_{i=1}^{N} ||A_i \omega_i Sin(\omega_i t - \theta_i)|| \quad watt \quad (10)$$

Where n is number of gravity weight pairs.
Based on Figure 4, it shows that each gravity weight delivers positive energy only on half period of ocean

waves. Therefore, equation (9) need to be further divided by 2. Hence, total energy produced by this proposed wave energy converter for irregular waves is half of the absolute value equation (9);

$$P = \frac{1}{2}n(M-m)g\sum_{i=1}^{N} A_i\omega_i Sin(\omega_i t-\theta_i)\,watt \qquad (11)$$

Equation (10) is over simplified of irregular ocean waves, therefore, the JONSWAP (Joint North Sea Wave Project) spectra is utilized for simulation[14].

$$P = \frac{1}{2}n(M-m)g\sum_{i=1}^{N} A_i S(\omega_i) \quad watt \qquad (12)$$

$$S(\omega) = \frac{\alpha g^2}{\omega^5} exp\left[-\beta\frac{\omega_p^4}{\omega^4}\right]\gamma^{\alpha} \qquad (13)$$

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

$$\sigma = \begin{Bmatrix} 0.07 \;\; if\ \omega \le \omega_p \\ 0.09\ if\ \omega > \omega_p \end{Bmatrix}$$

$$\beta = \frac{5}{4}$$

Where;

ω = wave frequency (2π/s)
ωp = The peak frequency(2π/s)
α = The intensity of the spectra.
γ = Peak enhancement factor
β = A shape factor

Simulation result of the proposed wave energy converter using irregular waves described in equation (11) are presented in Figure 5 and Figure 6 by means of MATLAB software[15].

3.0 DISCUSSION

One of the main goal of this study was an attempt to find the performance of the proposed wave energy converter under irregular wave condition. Result obtained shows that more wave power can be captured as seen on Figure 5 and Figure 6. These figures, illustrate the result of simulation using JONSWAP wave model in time domain that demontrate the variation of raw output power converted by four pairs of gravity weights as illustrated in Figure 2. These variation follow the irregular wave spectrum. Interstingly, the converted power resembles the full wave rectifier that produce potential energy.

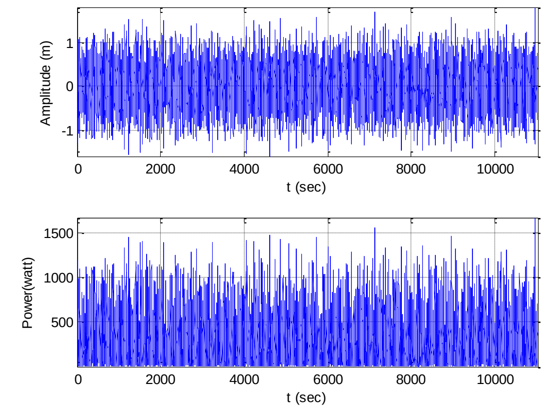


Figure 5 Matlab Simulation result using JONSWAP wave model with gravity weight (M) = 100 Kg, counter weight (m) = 5 Kg, wave height 2 m and peak period 6 second.

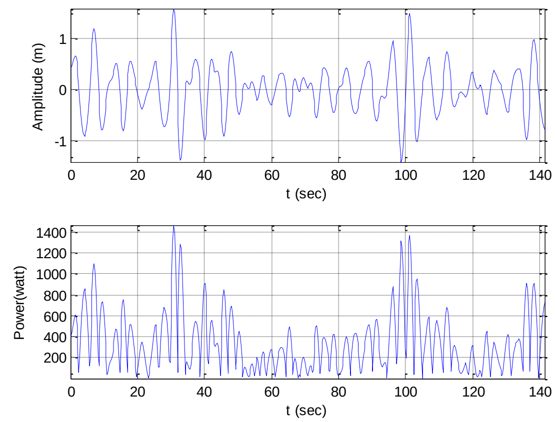


Figure 6 Close up of simulation result using JONSWAP weight (M) = 100 kg, counter weight (m) = 5kg, wave height 2 m and peak period 6 second.

Suprisingly, by changing the orientation of wave energy converter from harnessing bouyant force to gravity force using container filled with sea water gave significant output power. This simulation utilises four pairs of gravity weight. Each pairs weight is 100 kg (equal to 100 ltr of sea water), counter weight 5 kg and wave height peak to through is 2 m. The amount of produced power vary from 0.30 to 1.2 KW. However, this results need further validation by means of physical modelling in wave flume and real sea tests respectively. The limitation of this study was the assumption that the power losess due to mechanical friction of one way gears, gear box and generator were not taken into account. Therefore, these constraint need further studies.

4.0 CONCLUSION

Modelling of the interaction of one way gears wave energy converter with irregular ocean wave has been simulated using JONSWAP model and numerical computer software. It was found that the utilization of gravity force of gravity weight pairs of this converter produce significant power output. The pattern of output power was determined by the characteristic of irregular waves. Future work need to be done is to develop control model of this proposed wave energy converter to stabilize its output power.

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