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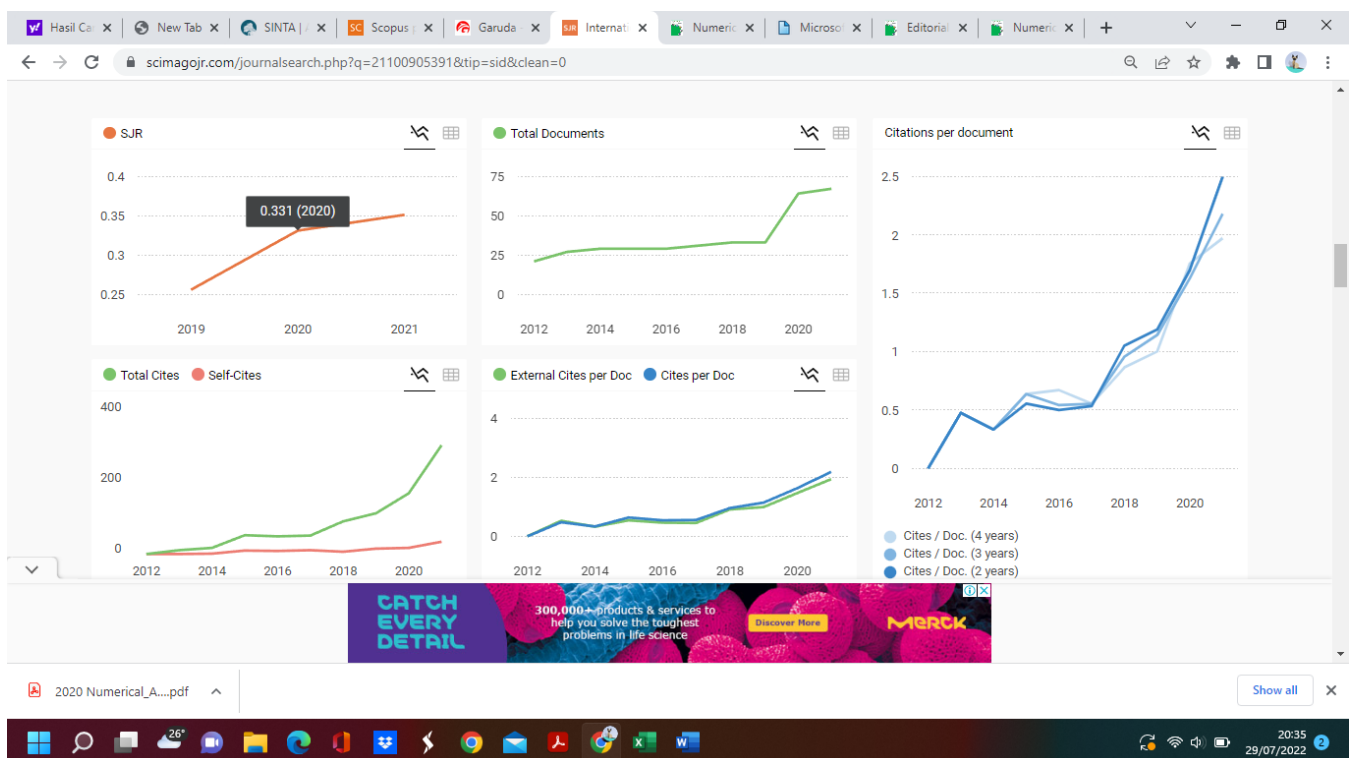
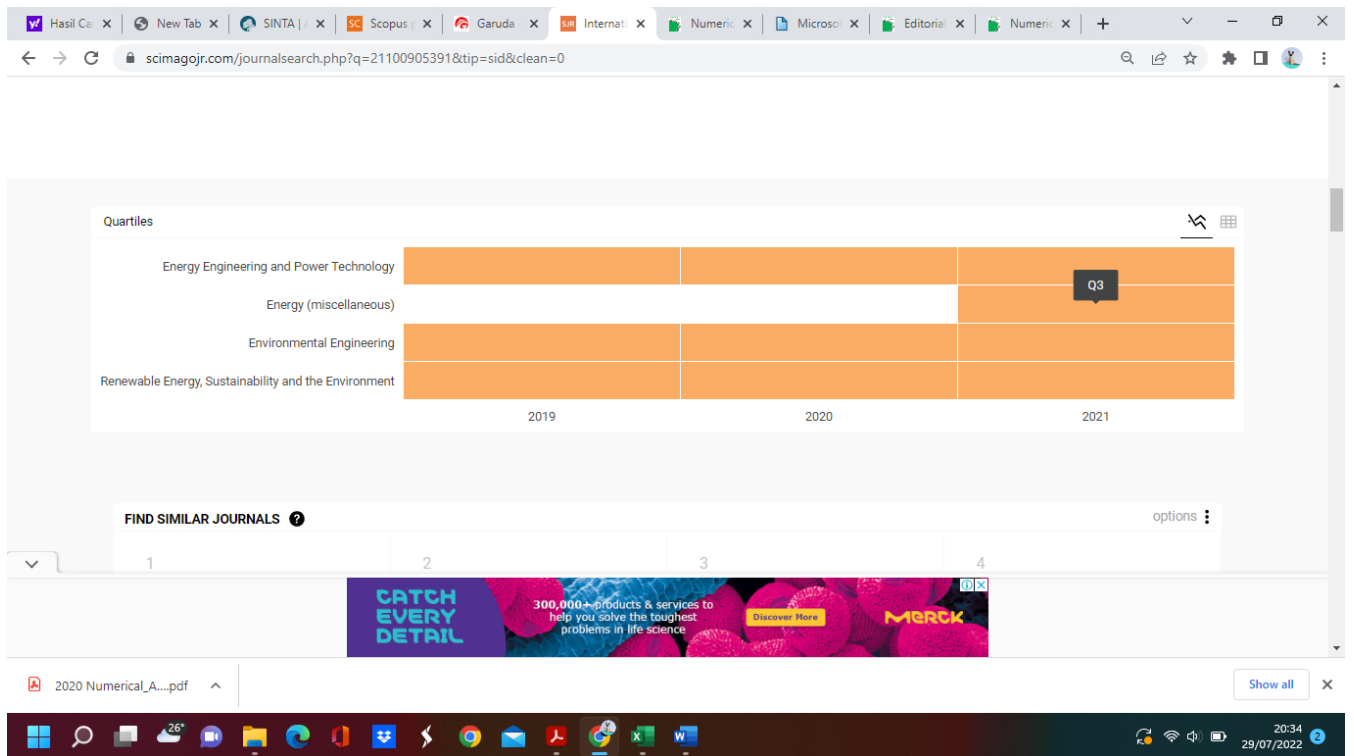
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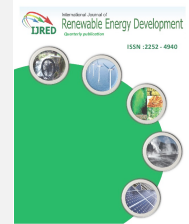




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Research Article

Numerical Analysis of Energy Converter for Wave Energy Power Generation-Pendulum System

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ABSTRACT. The wave energy power generation-pendulum system (WEPG-PS) is a four-wheeled instrument designed to convert wave power into electric energy. The first wheel is connected to the pendulum by a double freewheel, the second and third are ordinary wheels, while the fourth is a converter component that is axially connected to the electric generator. This design used the Euler-Lagrange formalism and Runge-Kutta method to examine an ideal dimension and determine the numerical solution of the equation of motion related to the rotation speed of the wheels. The result showed that the WEPG-PS' converter system rotated properly when its mass, length, and moment of inertia are 10 kg, 2.0 m, and 0.25 kgm², respectively. This is in addition to when the radius of the first, second, third, and fourth wheels are 0.5, 0.4, 0.2, and 0.01 m, with inertia values of 0.005, 0.004, 0.003, and 0.1 kgm². The converter system has the ability to rotate the fourth wheel, which acts as the handle of an electric generator at an angular frequency of approximately 500 - 600 rad/s. The converter system is optimally rotated when driven by a minimum force of 5 N and maximum friction of 0.05. Therefore, the system is used to generate electricity at an amplitude of 0.3 - 0.61 m, 220 V with 50 Hz. Besides, the lower rotation speed and frequency of the energy converter of the WEPG-PS (300 rad/s) and induction generator (50 Hz) were able to generate electric power of 7.5 kW. ©2020. CBIOR-IJRED. All rights reserved

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1. Introduction

The use of new and renewable energies originating from natural resources is indispensable for supporting electric power in remote areas (Tumiwa and Imelda, 2011). Over the decades, the promotion of clean, low cost and sustainable energies such as hydropower, solar, biomass, wind, geothermal, wave and tidal has been experienced rapid growth in terms of technology and commercialization (Arthouros, 2019; Beabpimai & Chitsomboon, 2019). Aminuddin *et al* (2016) reported that

wave energy is a better option for supporting the availability of electric power in Indonesia because the country's archipelago with ocean area is wider than the mainland. The sea wave is the low cost and green energy resources for developing a simple wave power energy generation (Nielsen, 2006; Aziz, 2006).

Therefore, it is important to carry out research and development on making wave energy to be more efficient and competitive to reduce the cost and complexity of implementing the system, especially in remote areas. The wheels configuration and dimension are very important

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parts of the WEPG-PS due to their ability to convert kinetic energy of the wave into mechanical power. However, it is difficult to design a wave energy converter to yield a high efficiency since it involves various formulations, computations, manipulations, and implementations (Aminuddin *et al*, 2015; Houékpoheha, 2015; Monteiro *et al*, 2017). Many studies on sea wave as renewable and sustainable electric power have been carried out in Europe using various converter types (Drew *et al*, 2009; Yu *et al*, 2016). The converter system of wave power energy generation which is generally developed in Indonesian seas are oscillating water column (Wijaya, 2010; Utami, 2012) and pendulum systems (Utomo *et al*, 2008; Drew *et al*, 2009).

The wave power energy generation works by converting the sea wave's inertial force to mechanical energy, which is further converted into electric power. This procedure is very simple and easy to implement in a location with stable sea wave which shakes the pontoon integrated with the pendulum to the double-freewheel. The function of the double-freewheel is to rotate several wheels connected to the electric generator. This system was named a wave energy power generation-pendulum system (WEPG-PS) (Nam *et al*, 2011; Murakami *et al*, 2014).

The physical concept closely associated with a circular motion formulation is the Euler-Lagrange formalism (Taylor, 2005; Umeyama, 2010). This equation has been successfully applied for analysing the equilibrium of the wheels on a bicycle (Meijaard *et al*, 2007). According to Roubicek (2014), the equation of motion obtained by applying Euler-Lagrange formalism is generally in the form of differential equations as the fundamental of calculus variation. Therefore, to determine some physical quantities related to the WEPG-PS design estimation, it is necessary to solve the numerical solution of the motion equations converter system in the differential form. One of the relevant cases associated with this system is the application of the Runge-Kutta method for solving the equations of motion in a hydraulic converter that has been successfully modelled and realized in a hydraulic wave energy converter (Plessis, 2012). The advantages of the Runge-Kutta method are iterative and sequential in the computational process (Naber, 2006; Aminuddin, 2008).

In this study, an ideal design and dimension of WEPG-PS was developed by employing the Euler-Lagrange formalism and Runge-Kutta method. The ideal configuration and dimensions of energy converter in generating electricity are signed by the optimal rotation speed of the wheel which is directly connected to the electric generator.

2. Methods

The designing process of the WEPG-PS (wave energy power generation-pendulum system) was carried out in three main steps. The first was by determining the coordinate system for the energy converter of WPG-SP. This was followed by formulating the equation of motion of the energy converter utilizing the Euler-Lagrange formalism. Finally, the dimension of the energy converter of WPG-SP was determined by solving the equation of motion using the fourth-order of the Runge-Kutta method.

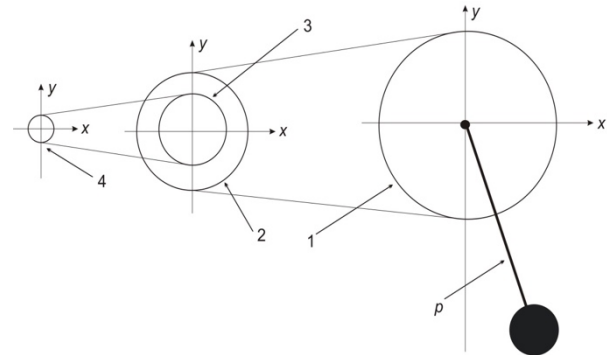


Fig. 1. The coordinate system of converter energy of WPG-PS which consist of 1 pendulum and 4 wheels. The first wheel is connected to the pendulum by a double freewheel, while the second and third are ordinary wheels. The fourth is a converter component axially connected to the electric generator.

The coordinate system used in this study was developed from a converter of wave power energy generation for the small wave amplitude (Utomo *et al*, 2008; Drew *et al*, 2009) and a principle of bicycle wheels (Taylor 2005; Meijaard *et al* 2007). However, the converter system of WEPG-PS improved in this study consists of one pendulum and 4 wheels connected to the same axis and chain with the electric generator. The first was a double freewheel connected to the same chain with the second which acts as a conventional wheel. Furthermore, the second wheel was connected to the same axis with the third which is also a regular wheel. Finally, the outside part of the third wheel was connected to the same chain with the fourth one in the same axis of the electrical generator as shown in Figure 1.

The coordinate system in Figure 1 is used for formulating dynamics equation of converter energy using Euler-Lagrange formalism which is developed from references (Meijaard *et al*. 2007; Roubicek, 2014). The Lagrange function described the difference between kinetic (T) and potential (V) energies as follows

$$T_p = \frac{1}{2} I_p \dot{\theta}_p^2 \quad (1)$$

$$V_p = -m_p g l \cos \theta_p. \quad (2)$$

Here, p-index means pendulum. Furthermore, for the wheels system, the potential energy equals zero ($V=0$) because the radius of wheels is constant. Consequently, the Lagrange function of the wheels system is based on kinetic energy. The equations below are the representation of kinetic energy for every first, second, third, and fourth wheel, respectively:

$$T_1 = \frac{1}{2} I_1 \dot{\theta}_1^2, \quad (3)$$

$$T_2 = \frac{1}{2} I_2 \dot{\theta}_2^2, \quad (4)$$

$$T_3 = \frac{1}{2} I_3 \dot{\theta}_3^2, \quad (5)$$

$$T_4 = \frac{1}{2} I_4 \dot{\theta}_4^2. \quad (6)$$

Assuming the initial rotation velocity of the pendulum is equal to the first wheel ($\theta_b < \theta_1$), the general Lagrange function is obtained as follows

$$L = \frac{1}{2} I_p \dot{\theta}_1^2 + \frac{1}{2} I_1 \dot{\theta}_1^2 + \frac{1}{2} I_2 \left(\frac{r_1}{r_2} \dot{\theta}_1 \right)^2 + \frac{1}{2} I_3 \left(\frac{r_1}{r_2} \dot{\theta}_1 \right)^2 + \frac{1}{2} I_4 \left(\frac{r_1 r_3}{r_2 r_4} \dot{\theta}_1 \right)^2 + m_p g l \cos \theta_p. \quad (7)$$

Here, the angular velocity of the pendulum and first wheel is represented as $\dot{\theta}_p$ and $\dot{\theta}_1$, respectively.

Furthermore, by using the Lagrange in equation (7) and involving the external force, the equations of motion energy converter is obtained as follows:

$$Q_n = Fl - m_p g l \sin \theta_p \quad (8)$$

$$\frac{\partial \dot{\theta}_p}{\partial t} = \frac{Fl - m_p g l \sin \theta_p - b \dot{\theta}_p^{(i+1)}}{I_p} \quad (9)$$

$$\frac{\partial \dot{\theta}_1}{\partial t} = \frac{Fl - m_p g l \sin \theta_p - b \dot{\theta}_1^{(i+1)}}{I_p + I_1 + I_2 \left(\frac{r_1}{r_2} \right)^2 + I_3 \left(\frac{r_1}{r_2} \right)^2 + I_4 \left(\frac{r_1 r_3}{r_2 r_4} \right)^2} \quad (10)$$

The parameters involved in the equation are the angular velocity of system ($\dot{\theta}$), thrust of sea wave (F), length of pendulum (l), mass of pendulum (mp), acceleration of gravity (g), friction of wheels (b), moment inertia of every wheels (I), and radius of all wheels (r). The differential equation for determining angular velocity of the second, third, and fourth are as follows:

$$\frac{\partial \theta_2}{\partial t} = \frac{r_1}{r_2} \dot{\theta}_1, \quad (11)$$

$$\frac{\partial \theta_3}{\partial t} = \frac{r_1}{r_2} \dot{\theta}_1, \quad (12)$$

$$\frac{\partial \theta_4}{\partial t} = \frac{r_1 r_3}{r_2 r_4} \dot{\theta}_1. \quad (13)$$

To analyse the angular speed of the WEPG-PS converter energy designed in Figure 1, the numerical solution of equation (9) and (10) as a representation of angular speed for the pendulum and first wheel is determined. The angular speed of the three other wheels is calculated based on the first wheel.

The four-order of the Runge-Kutta method was used to design an ideal configuration and dimension of the WEPG-SP energy converter. The algorithm of the Runge-Kutta method applied in this case is improved from references (Naber, 2006; Aminuddin, 2012; Plessis, 2012). The first step is the determination of the initial rotation speed ($\dot{\theta}^{(i)}$) using the span of numerical calculation (h). The h-value is obtained from the difference between initial time ($t(n)$) and the end time ($t(i)$) divided by the number of iteration (N) as:

$$h = \frac{t^{(n)} - t^{(i)}}{N} \quad (14)$$

Next, the constants of k_1, k_2, k_3 and k_4 are calculated based on the initial value of $f(t^{(i)}, \dot{\theta}^{(i)})$ and h through formulas below:

$$k_1 = hf(t^{(i)}, \dot{\theta}^{(i)}) \quad (15)$$

$$k_2 = hf\left(t^{(i)} + \frac{h}{2}, \dot{\theta}^{(i)} + \frac{k_1}{2}\right) \quad (16)$$

$$k_3 = hf\left(t^{(i)} + \frac{h}{2}, \dot{\theta}^{(i)} + \frac{k_2}{2}\right) \quad (17)$$

$$k_4 = hf(t^{(i+1)}, \dot{\theta}^{(i)} + k_3) \quad (18)$$

The $f(t^{(i)}, \dot{\theta}^{(i)})$ - function is the initial dynamics equations of both pendulum and first wheel. Therefore, the parameter $\dot{\theta}^{(i+1)}$ is representation of angular speed of pendulum and the first wheel for the next iteration at the time, t , which is computed using

$$\dot{\theta}^{(i+1)} = \dot{\theta}^{(i)} + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (19)$$

The results from equation (19) are used to calculate the angular speed of the second, third, and fourth wheels to formulate equations (11), (12), and (13), respectively. The algorithm was implemented in Matlab code simultaneously to describe all conditions which have been previously formulated.

3. Results and Discussions

The configured WEPG-PS energy converter is optimized by selecting some parameters. The first parameter associated with the dimension of the pendulum is the mass (m_p), length (L_p), and inertia (I_p). This is followed by the radius of wheels (r), where r_1, r_2, r_3 , and r_4 are the first, second, third, and fourth, respectively. The other significant parameters are friction of wheels (b) and thrust of wave forces (F). The results of the computational processes are plotted in the characteristic of the rotation speed for all wheels and swing of the pendulum.

The Matlab code was used to obtain the angular velocity used in the computational process based on physical parameter. The values retrieved are used to determine the ideal configuration and dimension of the WEPG-SP energy converter. From the configuration, the angular velocity is used to analyse mass, inertial, friction, and thrust.

3.1 Ideal Configuration of WEPG-PS

The first configuration between pendulum and wheels which was computed using the fourth-order of the Runge-Kutta method in Matlab is a configuration of $p > r_1 > r_2 > r_3 > r_4$ as shown in Figure 2. The length of the pendulum and the radius of wheels are 0.5, 0.3, 0.2 and 0.01 meter, respectively. Both forces of friction of converter and thrust of wave energies are 0.1 and 5 N. The mass of the pendulum is 5 kg and the length is 1.5 m with inertia 0.5 kg.m². The inertias of the first to fourth wheels are 0.04, 0.03, 0.02, and 0.1 kgm², respectively. The result of the calculation using the values mentioned above is expressed in the graph of angular velocity shown in Figure 3. The maximum angular velocity of the fourth wheel which is coupled with the electric generator is approximately 300-400 rad/s.

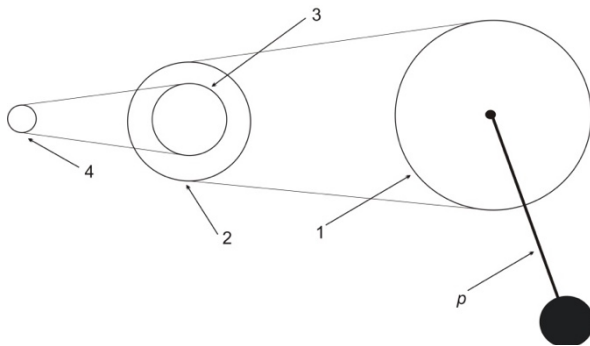


Fig. 2. Ideal configuration of energy converter.

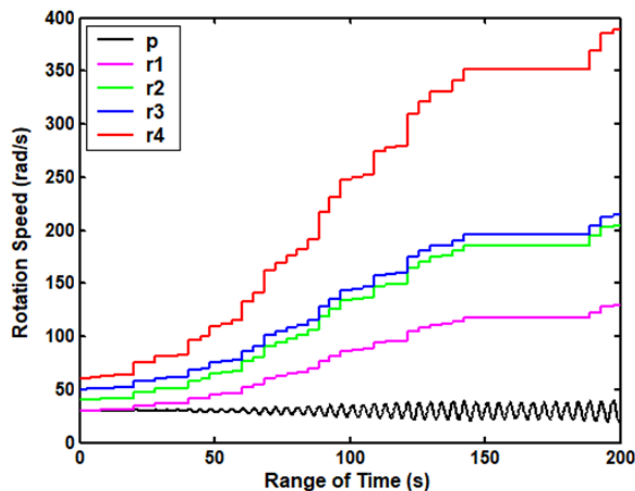


Fig 3. Angular velocity of energy converter with configuration of pendulum and wheels, $p > r_1 > r_2 > r_3 > r_4$. Here, the longest of the converter system is the length of the pendulum (p), followed by the first, second, third, and fourth wheels, respectively.

In comparison, the second analyzed configuration is $p > r_2 > r_1 > r_3 > r_4$ as shown in Figure 4. By employing almost the same parameters except for the radius and inertial of the first and second wheels, the angular velocity produced is lower than the first. The maximum angular velocity is shown in Figure 5 with 200-250 rad/s and constant at 200 s. Figure 4, shows that the second configuration has a maximum angular velocity lower than the first, therefore, the best configuration is $p > r_1 > r_2 > r_3 > r_4$.

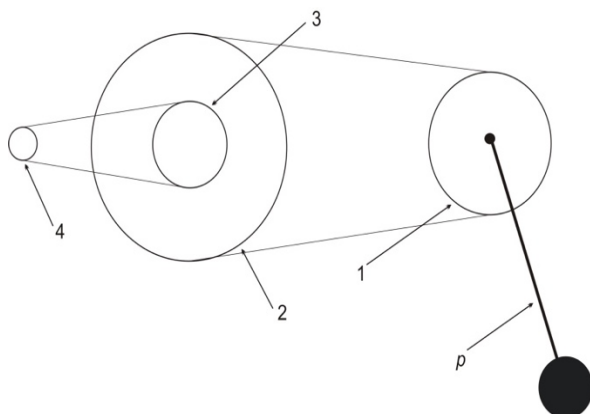


Fig. 4. Non-ideal configuration of energy converter.

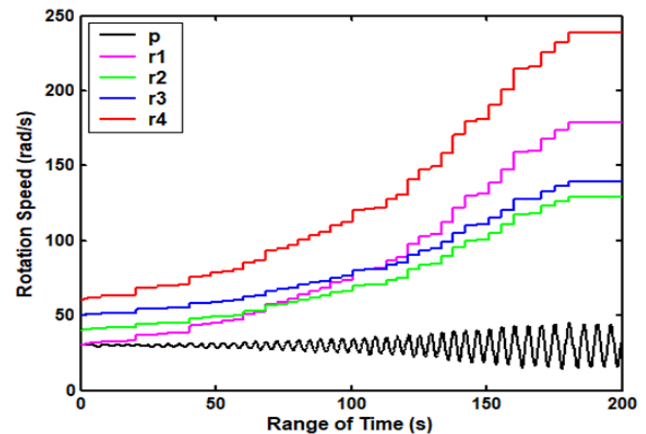


Fig. 5. Angular velocity of energy converter with configuration of pendulum and wheels, $p > r_2 > r_1 > r_3 > r_4$. This configuration is modified by setting the second wheel longer than other wheels followed by the first, third, and fourth wheels, respectively.

Table 1 shows the summary of the angular velocity of the whole energy converter system. The first configuration shown in Figure 2 is used as a reference to analyse several parameters affected by the angular velocity of the energy converter system. A significant increase of angular velocity is obtained when using the configuration and parameters as shown in Figures 2 and 3.

3.2 Dimension of pendulum

Both mass and length of pendulums are increased from 5 to 10 kg and 1.5 to 2.0 m, respectively. When the inertial of the pendulum is magnified from 0.05 to 1.00 kg.m², the angular velocity rapidly decreases. Conversely, an increase in angular velocity of the fourth wheel occurs when the pendulum's inertia is reduced from 0.5 to 0.25 kg.m². The significant enhancements of maximum angular velocity based on Figure 3 are from the ranges of 300 – 400 and 450 – 500 rad/s. The results show that the higher the mass and length of pendulums, the higher the angular velocity of the energy converter. However, an increase in inertia tends to decrease the angular velocity of the energy converter.

3.3 Radius and inertial of wheels

Treatment is conducted to both radius and inertial of wheels. In this simulation, the radius of the second- and third-wheels was 0.4 and 0.3 m, respectively. Meanwhile, the first and fourth wheels are similar to the previous computations at 0.5 and 0.01 m. Also, the number of wheels' inertial is sharply minified except for the fourth. The values of inertias for the first, second, and third wheels in this computation process are 0.005, 0.004, and 0.003 kgm², respectively.

The results show that the maximum angular velocity of the fourth wheel which was originally in range of 450 - 500 rad/s increased to 500 – 600 rad/s. This condition shows that there was a significant effect in radius for both the second-and third-wheels. In addition, the angular velocity of the fourth wheel is faster when the inertial of the system which is sharply reduced.

Table 1

The summary of numerical analysis using the mass (m_p) in meter (m), length (L_p) in meter (m), and inertia (I_p) in kilogram meter square (kgm²) of pendulums. The radius of the first to the fourth wheels (r_i) is in meter (m). Both friction of wheels (b) and thrust of wave forces (F) are in Newton (N). The main target is the maximum of the angular velocity of the fourth wheel (ω_4) is in radian per second (rad/s).

m_p	L_p	I_p	r_1	r_2	r_3	r_4	I_1	I_2	I_3	I_4	F	b	ω_4
5.0	1.5	0.50	0.5	0.3	0.2	0.01	0.04	0.03	0.02	0.1	5.0	0.10	400
5.0	1.5	0.50	0.4	0.5	0.2	0.01	0.03	0.04	0.02	0.1	5.0	0.10	250
10.0	2.0	1.00	0.5	0.3	0.2	0.01	0.04	0.03	0.02	0.1	5.0	0.10	300
10.0	2.0	0.25	0.5	0.3	0.2	0.01	0.04	0.03	0.02	0.1	5.0	0.10	500
10.0	2.0	0.25	0.5	0.3	0.2	0.01	0.05	0.04	0.03	0.1	5.0	0.10	600
10.0	2.0	0.25	0.5	0.3	0.2	0.01	0.05	0.04	0.03	0.1	10.0	0.05	800

3.4 Discussion

The promotion of new and renewable energy which originated from natural resource was conducted through the development of a wave energy power generation-pendulum system (WEPG-PS) (Nam *et al.*, 2011, Murakami *et al.*, 2014). This study employed a mathematical physics concept to formulate the equation of motion through Euler-Lagrange Formalism (Roubicek, 2014). Furthermore, the dimension of the converter energy of WEPG-PS is analysed based on the fourth order of the Runge-Kutta method which has an iterative and sequential computational process (Plessis 2012; Naber, 2006 and Aminuddin, 2008).

The result of this numerical analysis shows that the WEPG-PS' converter system rotated properly when several numbers act as a representation of the component's size. The pendulum mass, length and moment of inertia are 10 kg, 2.0 m, and 0.25 kg.m², respectively. The radius of the first, second, third, and fourth wheels are 0.5, 0.4, 0.2, and 0.01 m, with inertia approximately 0.005, 0.004, 0.003, and 0.1 kg.m², respectively. The converter system rotates the fourth wheel of the electric generator in the maximum angular velocity approximately 500 - 600 rad/s. The forces of friction of converter and thrust of wave energies chosen in the computational process are 0.1 and 5 N, respectively.

The WEPG-SP was configured based on the numerical analysis of $p > r_1 > r_2 > r_3 > r_4$. The longest converter system is the length of pendulum (p), followed by the first, second, third, and fourth wheels, respectively. The result is confirmed with several wheels configuration in theoretical mechanics which was successfully applied for analysing the equilibrium of the wheels on a bicycle (Meijaard *et al.*, 2007). The equation obtained in this study is closely associated with a circular motion of wheels using Euler-Lagrange formalism (Taylor, 2005; Umeyama, 2010; Roubicek, 2014).

The last parameter analyzed in this simulation is the influence of the forces friction and thrust wave energy to the angular velocity of the converter system. It is generally known in theoretical mechanics that the frictional force always holds up the velocity of the system. On the other hand, the thrust force upgrades the velocity of movement (Taylor, 2005). The computation process is used to prove both principles by increasing the value of the thrust force and decreasing friction. Besides, the numerical analysis for WPEG-SP in this study is appropriate with the other

previous studies of the pendulum system in refs (Nam *et al.*, 2011, Yu *et al.*, 2016).

The converter system optimally rotated when the system is driven by a force of 10 N and friction of 0.05. The system is easily implemented when the loss associated with the driven force is approximately 5%, Tat wave amplitude of 0.3 - 0.6 m (Aminuddin *et al.*, 2016; Sheng, 2019). It is possible to use WEPG-PS as a system for generating electricity at about 220 Volt with frequency of 50 Hertz because Indonesia seas potentially produces an amplitude average of sea waves approximately 0.30-0.50 m (Gupta, 2012; Supardi *et al.*, 2014). The same parameters have been implemented in Indonesian but different designs (Utomo *et al.*, 2008; Utami, 2012).

Theoretical estimation was carried out to obtain the power of the WEPG-PS design analyzed in this study. The physical concept correlated to this calculation is the induction generator which generates electrical energy from mechanical sources, by using electromagnetic induction. This process is known as a power plant. The generator works on the principle of electromagnetic induction which occurs when a coil or solenoid is moved on a magnet. The solenoid is a cylindrical coil of wire whose distance between turns is very tight. Both objects produces electromagnetic induction generally known as electromotive forces (Jackson, 1998, Irasari *et al.*, 2006). The illustration of induction is shown in Figure 9.

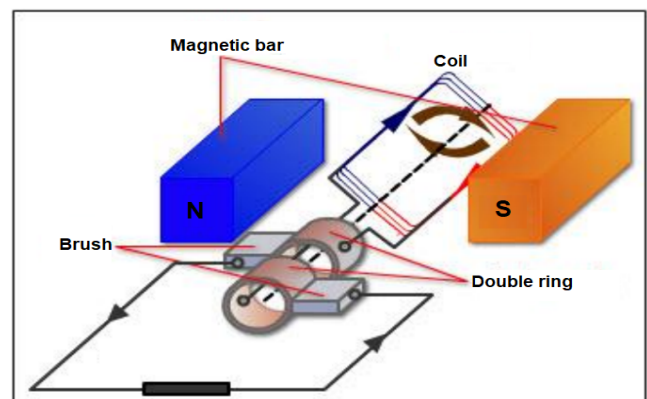


Fig. 9. An induction generator with a magnetic bar (north and south pole), coil, brush and double ring.

Several types of induction generators are widely used in renewable energy power plants due to their lower price, no need for brushes, simple construction, as well as easy

and inexpensive maintenance (Caxaria, 2011). The dimensions of the coil, magnitude of magnetic field on a generator, and the speed of movement varies based on the desired electrical power requirements (Irasari *et al*, 2006). The mathematical formulation of the electromotive force is represented as:

$$\varepsilon = N B A \omega \sin \theta. \quad (20)$$

Where parameters of ε , N , A , ω , and θ are the electromotive force in, number of coils, the cross-section area of the generator, rotation speed of solenoid, and magnitude of the angle between the magnetic field and moment. Electromotive force of 220 Volt is used to compensate the voltage which is generally used to design electric pans in small scale (Irasari *et al*, 2006). The correlation between the electric power (P) and current (I) to the electromotive force is calculated as follows

$$P = \varepsilon I. \quad (21)$$

Both equations (20) and (21) are reduced for estimating the electric power based on rotation speed (ω) and frequency (f)

$$P = \omega f \times \eta. \quad (22)$$

The addition of the efficiency factor (η) is developed from the optimization principle of generator rotation for small hydropower (Irasari *et al* 2010). The efficiencies of the small hydropower plant in the previous study are approximately 80-90% (Jorfri, 2009). Therefore, the energy converter rotation of the WEPG-PS in this study is lower than the hydropower, with an efficiency factor of 50%.

Tables 2 and 3 show the estimated value of the electric power of WEPG-PS using equation (22). In the previous calculation, the frequency of the electric generator was 50 Hertz. However, this research employed the rotation speed from the numerical analysis in Table 1. Furthermore, the electric power in the former step was computed using the lower rotation speed of 300 rad/s with varying frequencies

Table 2
The electric power and rotation speed

Rotation speed (rad/s)	Electric power (kW)
300	7.5
400	10.0
500	12.5
600	15.0
700	17.5
800	20.0

Table 3
The electric power and frequency

Frequency (Hz)	Electric power (kW)
50	7.5
60	9.0
70	10.5
80	12.0
90	13.5
100	15.0

Both estimations are performed in the assumption that the energy loss of the WEPG-PS is 50%. The results showed that the lower rotation speed and frequency of the energy converter of the WEPG-PS (300 rad/s) and induction generator (50 Hz) generates electric power of 7.5 kW (Gupta, 2012; Supardi *et al*, 2014). The theoretical calculation confirmed the result of the previous WEPG (Utomo *et al*, 2008; Drew *et al*, 2009; Utami, 2012). Therefore, in implementing the system, the performance is improved by reducing the loss and increasing the rotation speed.

4. Conclusion

In conclusion, this research carried out a numerical analysis to determine an ideal configuration and dimension of the WPEG-PS. The Euler-Lagrange, was used to obtain the motion equation of the converter energy in the differential equations. Furthermore, the numerical solution of the differential equation results from several parameters was used to attain the angular velocity of the wheel which is directly connected to the electric generator.

The forces of friction and wave inertial are 0.025 and 10 N, while the maximum angular velocity achieved was 700-800 rad/s by employing several physical parameters and the converter as $p > r1 > r2 > r3 > r4$. The mass, length, and inertia of pendulum are 5 kg, 2 m and 0.25 kgm² respectively. In addition, the best radius of the first to fourth wheels are 0.5, 0.4, 0.3, 0.2 and 0.01 meter, with inertia values of 0.04, 0.03, 0.02, and 0.1 kgm².

The parameter used to achieve optimal configuration and dimension in is the computational process. Therefore, the other number with maximum velocity higher than 400-500 rad/s, needs to be targeted. Besides, to prove the validation of the numerical analysis, the design needs to be implemented by developing the real WPEG-SP based on the optimal dimension retrieved from numerical analysis. Also, through the electric power estimation, the lower rotation speed and frequency of energy converter of the WEPG-PS (300 rad/s) and induction generator (50 Hz) were still able to generate electric power 7.5 kW.

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