Design of Ocean Wave Power Plant with a Two-Axis Vertical Pendulum Mechanism System

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Abstract. Renewable energy is a promising potential for the future, where this energy is low emission and environment friendly. One of the renewable energies that are abundant and rarely used is ocean waves. Energy from ocean waves can be extracted using an ocean wave power plant with a pendulum system (PLTGL-SB). The main components of PLTGL-SB are pontoon and pendulum, where the pendulum will oscillate when ocean waves hit the pontoon. This research will analyze PLTGL-SB with a two-axis mechanism. The analyzes were performed with simulations using CFD applications (computational fluid dynamics) and only used three degrees of freedom (pitching, rolling, and heaving). The design of PLTGL-SB has a length of 2.2 m, a width of 1.3 m, a height of 1.61 m, and an overall mass of 199.5 kg with two axes and two pendulums on each axis. The highest simulation results obtained a maximum deviation angle of 32.31° and an angular velocity of 1.44 rad/s with 10 kg pendulum mass and 1.0 m pendulum length at 0.5 m wave amplitude. If this design is used in the rumah apung Bangsring, it will require seven modules of PLTGL-SB and two additional 12V 50Ah batteries.

1. Introduction
Ocean energy is separated into three types: ocean current energy, ocean thermal energy, and ocean wave energy. According to mapping done by Balitbang, the Kementerian Energi dan Sumber Daya Mineral Republik Indonesia in 2014, ocean current energy has a practical potential of 17.989 MW, marine thermal energy has a practical potential of 41.001 MW, and ocean wave energy has a practical potential of 1.995 MW spread over ten straits in Indonesia: Riau Strait, Toyapakeh Strait, Alas Strait, Sunda Strait, Lantaruka Strait, Pantar Strait, Boleng Strait, Raja Ampat Mansuar Strait and Molo Strait [1]. Oscillating Water Column (OWC), Oscillating Wave Surge Converter, Submerged Pressure Differential, Overtopping Device, Salter's Duck System, and other methods can extract ocean waves [2]. Zamrisyaf initially developed PLTGL-SB in 2002, and it was developed utilizing the pendulum mechanism in Indonesia. In 2010, Zamrisyaf experimented using a rectangular pontoon with a horizontal pendulum mechanism and a vertical pendulum that can produce 25.2kW in each pendulum. The pendulum mass is 10 kg, the arm length is 2 meters, and the wave period is 3 seconds with a wave amplitude of 1.5 meters [3]. In 2016, an experiment was conducted at the laboratory 1:10 using an outrigger pontoon to analyze the characteristics of a one-axis pendulum, obtaining a maximum pendulum deviation of 60° with a length of the arm of 106.7 mm and a pendulum mass of 20 grams at a wave period of 0.8 seconds. In 2018, a simulation was performed using the CFD application to obtain a one-axis pendulum motion response with an outrigger pontoon, obtaining a pendulum
deviation of 23.5° with an arm length pendulum of 10.67 cm and a mass of 19.9 grams in a wave period of 0.8 seconds. In 2020, a simulation was carried out using the CFD application. The pontoon catamaran and pendulum one axis got a maximum 20° deviation with an arm length of 1.25 m, and the mass of the pendulum is 100 kg at a wave period of 7 seconds and amplitude of 0.1 m. [4] [5] [6]. The PLTGL-SB concept is to use the oscillating motion of ocean waves to oscillate the pendulum. An electric generator can convert the energy generated by pendulum motions into electrical energy. The amount of energy that can be extracted is strongly influenced by the period and amplitude of the ocean waves. Other factors that affect the torque and rotation value in energy conversion are the length and weight of the pendulum [7]. PLTGL-SB can also be utilized to generate electricity on floating marine structures for aquaculture, conservation, and marine ecotourism. In this research, a PLTGL-SB vertical pendulum with a two-axis mechanism will be designed to develop the PLTGL-SB that has been researched previously.

2. Method
2.1. Design of PLTGL-SB with two-axis mechanism
The catamaran pontoon on the PLTGL-SB measures 2.1 meters long, 1.2 meters wide, and 0.4 meters high. It has a 0.137 m design draft and a mass displacement of 199.5 kg. Two vertical axes with two pendulums on each axis are used in the PLTGL-SB.

![Perspective view of PLTGL-SB with two-axis mechanism](image1)

![Dimensions of PLTGL-SB with two-axis mechanism](image2)

2.2. Meshing
Meshing is the splitting of an object into several elements to obtain accuracy in a simulation. The defeaturing tolerance and maximum element size values are determined in this setting; the larger the value used, the less accurate the analysis results. The determination of these two values can also affect the maximum limit of the use of the frequency value allowed in the model; the smaller the value used,
the greater the frequency limit. In this simulation application, the number of elements is limited to 18,000 elements.

Table 1. Meshing parameter

| Detail meshing         |       |
|------------------------|-------|
| Defeaturing tolerance  | 0.001 m |
| Maximum element size   | 0.05 m |
| Total nodes            | 7656  |
| Total elements         | 7542  |

2.3. Simulation process
The simulation process is divided into two phases. The first phase is to simulate the pontoons to obtain a response to motion caused by ocean waves, and the second phase is to use the pontoon responses data to obtain a pendulum motion response. The direction of the 0° angle wave in this simulation is on the object's x-axis. This simulation only uses three degrees of freedom to obtain data on the pontoon's response to waves: RX (rolling), RY (pitching), and GZ (heaving). In the first phase, wave characteristics use a regular wave with amplitudes of 0.1 m, 0.3 m, and 0.5 m, a wave period of 3 seconds, and a wave direction of 45°.

2.4. Result Analysis
The deviation and angular velocity of pendulums are the output data from the simulation process. Equation 1 can be used to calculate the mechanical power of rotational motion. The value of the torque (τ) and the pendulum's angular velocity (ω) are strongly influenced by the deviation of the pendulum from the equilibrium point based on the pendulum's motion.

\[ P = \tau \omega \]  \hspace{1cm} (1)

\[ \tau = mg \sin \theta \]  \hspace{1cm} (2)

According to equation 2, the torque value will be more prominent as the pendulum's deviation increases. On the other hand, the highest angular velocity occurs when the pendulum is at equilibrium, based on the mechanical energy of pendulum motion.

3. Result and Discussion

3.1. Two-axis pendulums motion
Based on the experimental result, it was found that the motion of the two-axis system is that the two axes will move opposite and complement each other on the positive side of the movement of one of the pendulums when the pendulum is on a negative side. The pendulum's motion on the y-axis will fill the positive side when the x-axis pendulum is on the negative side; the opposite applies. Figure 1 is a graph of the deviation angle of the experimental pendulum two. It found that the movement of pendulum 2 and pendulum 4 moves in opposite directions, and the movement of pendulum 1 and pendulum 3.
3.2. Effect of wave amplitude to pendulum motion

The impact of wave amplitude on the motion of pendulums is analysed. 0.1 m, 0.3 m, and 0.5 m wave amplitudes were used in the experiments. The maximum and minimum deviation is 6.33° and -6.32° on wave height 0.1 m. Maximum deviation at 0.1 m, 19.15° with a minimum deviation of -19.09° at 0.3 m, and maximum deviation 32.31° with a minimum deviation of -31.99° at 0.5 m, as shown in figure 4. The pendulum's angular velocity in these experiments is 0.27 rad/s, 0.84 rad/s, and 1.44 rad/s, respectively, at wave amplitudes of 0.1 m, 0.3 m, and 0.5 m, as shown in figure 5. The deviation and angular velocity of pendulums will increase as the wave amplitude increases, according to this study of the effect of wave amplitude on pendulum motion.

![Figure 3. Two-axis pendulums motion](image)

![Figure 4. Effect of wave amplitude to pendulum’s deviation angle](image)

![Figure 5. Effect of wave amplitude to pendulum’s angular velocity](image)
3.3. **Effect of pendulum’s mass on its motion**

The impact of a pendulum's mass on its motion is analyzed. 0.3 m wave amplitudes are used in experiments with pendulum masses of 10 kg and 5 kg. The maximum deviation using 10 kg mass pendulums is 19.15° with a minimum deviation of -19.09°, while the maximum deviation using 5 kg mass pendulums is 16.69° with a minimum deviation of -16.67°. The angular velocity of the pendulum in these experiments is 0.84 rad/s and 0.74 rad/s, respectively, with pendulum masses of 10 kg and 5 kg. The pendulum's mass on its motion was analyzed, and it was found that as increasing the pendulum's mass, then the deviation and angular velocity of the pendulums will increase, as shown in figures 6 and 7.

![Figure 6. Effect of pendulums mass to its deviation angle](image)

![Figure 7. Effect of pendulums mass to its angular velocity](image)

3.4. **Effect of pendulum’s length on its motion**

Analysis effect of pendulums length to its motion uses experimental data with pendulum length 1.0 m and 0.5 m at wave amplitudes of 0.5 m. With 1.0 m length of pendulums, the maximum deviation is 32.30° with a minimum deviation of -31.99° and using 0.5 m length of pendulums, and the maximum deviation is 21.60° with a minimum deviation of -21.56°. In these experiments, the angular velocity of the pendulum with pendulums lengths of 1.0 m and 0.5 m is 1.43 rad/s and 0.80 rad/s, as shown in figure 8. The analysis of the effect of the pendulum's length on its motion found that as the pendulum's length increases, its deviation and angular velocity will increase, as shown in figure 6 for deviation and figure 9 for angular velocity.
3.5. Power Calculation
The value of deviation and the angular velocity of the pendulum are the experimental output data. The value of power production is calculated using these data and mathematical calculations. Based on the experimental data, the highest power production in the experiment was obtained with an amplitude value of 0.5 m and wave period of 3 seconds, generating power on the x-axis up to 77.38 watts and on the y-axis up to 44.91 watts. Table 2 shows the power output for all variations.
Table 2. Variation power output

| Pendulum Mass [kg] | Pendulum Length [m] | Wave Amplitude [m] | Power at X-axis [W] | Power at Y-axis [W] |
|--------------------|---------------------|-------------------|---------------------|---------------------|
| 0.5                | 0.1                 | 0.20              | 0.12                |
| 0.5                | 0.3                 | 1.81              | 1.08                |
| 0.5                | 0.5                 | 2.97              | 1.98                |
| 1.0                | 0.1                 | 1.20              | 0.74                |
| 1.0                | 0.3                 | 10.79             | 6.82                |
| 1.0                | 0.5                 | 30.42             | 19.24               |
| 1.0                | 0.5                 | 15.61             | 8.14                |
| 0.5                | 0.1                 | 3.09              | 1.69                |
| 0.5                | 0.3                 | 27.85             | 15.44               |
| 0.5                | 0.5                 | 77.38             | 44.91               |

3.6. Application of PLTGL-SB on rumah apung Bangsring.
Rumah apung Bangsring is one of the ecotourism floating buildings in coral reef conservation, fish culture, and diving tourism, located in Banyuwangi, East Java, 100 meters off the Bangsring shoreline. At night, this floating structure requires electricity to power the lights, which total 225 watts. According to data from the Badan Meteorologi Klimatologi dan Geofisika, the water area around the rumah apung Bangsring has a wave height of 0.5 m and a wave period of 3 seconds.

3.6.1. Power Production. Using the related wave characteristics data, the maximum displacement of the pendulum is 32.31° with an angular velocity of up to 1.44 rad/s, as shown in Figures 10 and 11. The obtained power output is 77.38 watts on the x-axis and 44.91 watts on the y-axis utilizing mathematical calculations as shown in 12.

Figure 10. Deviation angle of pendulum no. 1 at rumah apung Bangsring water areas
3.6.2. *Generator and gearbox calculation* A generator with a rating of 100 watts and a speed of 600 rpm is chosen based on power production calculations. A gearbox is required to satisfy the generator's rotation and torque needs. Rotation and torque are inverses, the greater the rotation, the lower the torque. It also applies to the gear mechanism. It can be formulated as equation 3.

\[ \frac{N_{\text{input}}}{N_{\text{output}}} = \frac{T_{\text{output}}}{T_{\text{input}}} \]  

(3)

The two-axis mechanism works used a gearbox with a 1:67.5 ratio, which comprises a combination of spur and bevel gear. The maximum output power is 69.64 watts with a torque of 1.07 Nm and a speed of 57.75 rad/s or 620.43 rpm using the gearbox efficiency value of 0.9.

| Table 3. Generator specification |
|---------------------------------|
| Parameters | Value |
| Rating power | 100 watt |
| Maximum Power | 140 watt |
| Voltage | 24 volt |
| Speeds | 600 rpm |
| Start Torque | 0.08 Nm |
Table 4. Gearbox parameters design

| Parameters                  | Value          |
|-----------------------------|----------------|
| Gearbox efficiency          | 0.9            |
| Gearbox ratio               | 1: 67.5        |
| Torque input                | 104.75 Nm      |
| Torque output               | 1.55 Nm        |
| Speed Input                 | 13.70 rpm (1.44 rad/s) |
| Speed Output                | 832.53 rpm (87.18 rad/s) |
| Speed Output (at rating power) | 620.43 rpm (64.97 rad/s) |

Figure 13. Two-axis mechanism gearbox design

The output rotation is obtained by using a gearbox on a two-axis mechanism to rotate the generator with fluctuating values in the same direction. As shown in figure 14, the rotational speed ranged from 0-800 rpm, with the peak rotation speed repetition occurring every five seconds. The amount of power produced varies depending on the rotational speed, as shown in figure 15. Based on the graphic data, the PLTGL-SB module can extract 18.2 Wh of energy in one hour and up to 437 Wh in one day.

Figure 14. Angular velocity output
3.6.3. *Rumah apung Bangsring’s power analysis* Rumah apung Bangsring's power analysis Based on the previous analysis, the output power is 69.64 watts, and it can extract up to 437 Wh of energy for 24 hours. At night, 2700 Wh of energy is required to light all the lights with a total power of 225 watts for 12 hours. According to the calculations, need 7 PLTGL-SB modules are required for all of the lamps in the rumah apung Bangsring, with two additional 12V 50Ah batteries.

4. Conclusion

Based on the research outcome of the design of ocean wave power plant with a two-axis vertical pendulum mechanism system. It can be concluded as follows:

1. With pendulums' two-axis mechanism, obtained pendulums at x-axes will move opposite with pendulums at the y-axis and complement each other.
2. The pendulum's deviation and angular velocity will increase as the wave amplitude increases. In the exact specification of pendulums, a maximum deviation of 6.33° with angular velocity up to 0.27 rad/s was obtained in the experiment at a wave amplitude of 0.1 m. In comparison, a maximum deviation of 32.31° with angular velocity up to 1.44 rad/s was obtained in an experiment with wave amplitude 0.5.
3. The pendulum's mass on its motion is that as the pendulum's mass becomes heavier than the previous, the deviation and angular velocity of the pendulums will increase. In the same wave amplitudes, using 10 kg mass pendulums obtained a maximum deviation of 19.15° with an angular velocity of 0.84 rad/s, while using 5 kg mass pendulums obtained a maximum deviation of 16.69° with an angular velocity of 0.74 rad/s.
4. The effect of the pendulum's length on its motion is s the length of the pendulum increases; the deviation and angular velocity of the pendulums increase. In the same wave amplitudes, pendulums of length 1.0 m obtained a maximum deviation of 32.30° with angular velocity up to 1.44 rad/s. In comparison, pendulums of length 1.0 m obtained a maximum deviation of 21.60° with angular velocity up to 0.80 rad/s.
5. The highest pendulum extraction power is 77.38 watts on the x-axis and 44.91 watts on the y-axis.
6. The maximum power generated was 69.64 watts at 620.43 rpm using a 1:67.5 gearbox ratio and 0.9 efficiencies. This module can produce 18.2 Wh of energy in an hour and 437 Wh in a day. Seven pcs of PLTGL-SB and two pcs 12V 50 Ah batteries are used to fulfill the 2700 Wh energy needs for lighting the rumah apung Bangsring.

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