

Analysis of a Single Vertical Pendulum Mechanism on the Pontoon-Boat as a Wave Energy Harvester

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Abstract

The aims of this study are to model the wave energy harvester device using a single pendulum on a pontoon called Single Vertical Pendulum Mechanism (SVPM) and analyze the voltage generated by the mechanism. The simulation method was conducted in order to provide the power generated by SVPM. The SVPM's dimension was designed on a laboratory scale and the wave amplitude was adjusted by the amplitude on the laboratory pool. The mechanism model uses wave energy as the excitation force of the pendulum. The pendulum oscillates, and drives the transmission gear which transmits the force to the generator. The generator produces electrical energy. The variation used in the simulation was the mass of the pendulum, the length of the pendulum's arm, and the wave amplitude. The maximum power that can be generated by SVPM was 5,735 Watt occurred when the arrangement of SVPM was using the pendulum mass of 0,75 kg and the pendulum length of 0,2 m. The parameter that most affect the generated power of SVPM was the wave amplitude.

Keywords: wave energy harvester, pendulum, electrical energy, simulation method

1. Introduction

Wave energy is one of renewable energy which its source is accessible because the earth consists of mostly 70 percent of the ocean [1]. The feasibility studies of the wave's potential energy in several countries have been conducted [2] [3] [4]. The potential energy that is able to be harvested from the ocean's wave is approximately 885 TWh [5]. The potential energy of wave ocean varies based on the wave energy density. Theoretically, around 29,500 TWh/year is the potential energy of wave ocean which its density is over 5kW/m [6]. Moreover, approximately 93,000 TWh/year could be generated from worldwide wave [6].

Based on the potential energy from ocean waves, the systems which could convert the energy of wave into electrical energy have been studied. Wave Energy Converters (WEC) which have three types, i.e. oscillating-body WEC, oscillating water column (OWC), and the last, overtopping device [7] were one of the methods to harvest the wave energy. The study about the oscillating-body WEC which used the parabolic openings as the wave reflector has been conducted [8]. The result showed that the parabolic opening on the oscillating-body WEC can amplify the heave response three times higher than the conventional opening. The most economic value (the cost of maintenance and utilization) among those three types of WEC is the overtopping device which can be installed at the shoreline [9]. The overtopping WEC has been mod-

eled using reservoirs in front of breakwater structures to generate electricity [10]. Piezoelectric was installed on the wave energy harvester device to generate more power than the conventional device [11] [12] [13] [14]. The floating buoy with the piezoelectric installation, generated power up to 103 W at the wave amplitude of 2 m [11]. The using of piezoelectric on an offshore-buoys has been studied and it concluded that the wave energy harvesting system was more efficient at the low frequency and high amplitude of wave [12]. The generated power of wave energy harvester device can be improved by adjusting the piezo-lens [12]. The electrical power of 25W/day can be generated by one painted flexible piezoelectric device which consists of flexible material and piezoelectric paint [14].

The aim of this study is to model a mechanism which able to harvest the wave energy. This study was using the oscillating-body WEC principal. The small pontoon was used as the oscillating-body which consists of a single vertical pendulum, transmission gear, and generator. The effects of the mass of the pendulum, the length of the pendulum's arm, and the wave amplitude to the generated voltage were analyzed too.

2. Theoretical Method

The design of wave energy harvester called Single Vertical Pendulum Mechanism (SVPM) is shown in fig. 1 which consists of (1) pendulum, (2) pendulum's arm, (3) sprocket, (4) bearing, (5) generator, (6) gear transmission,

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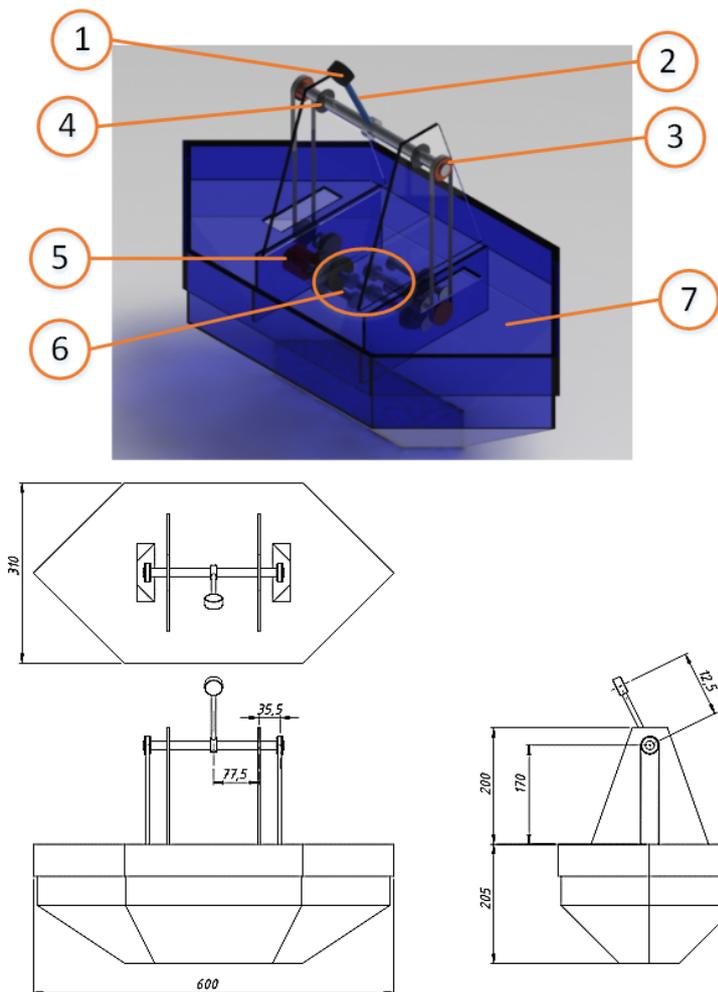


Figure 1. The design of a Single Vertical Pendulum Mechanism on the Pontoon-boat

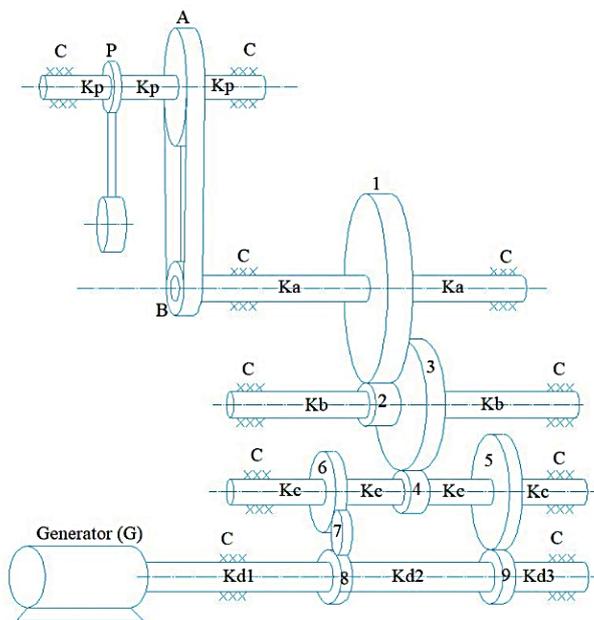


Figure 2. The angular displacement of the pendulum

and (7) pontoon-boat. The design of the mechanism was on the laboratory scale. While the dynamics model of the transmission of the harvester system is presented in fig. 2. The motion of wave agitates the pendulum to oscillate and then drives the gear transmission which is transmitted

the input force to the generator. The electrical energy is generated by the generator. The potential energy provided by pontoon mechanism was simulated.

The motion equations of the simulation method are stated below:

$$\left(M_p + \frac{1}{3}Mb\right)l^2.\ddot{\theta}_p + C.\dot{\theta}_p + \left[K_p + \left(M_p + \frac{1}{2}Mb\right)g.l\right].\theta_p + C.(\dot{\theta}_p - \dot{\theta}_A) + K_p.(\theta_p - \theta_A) = 0 \quad (1)$$

$$J_A.\ddot{\theta}_A + C.\dot{\theta}_A + K_p.\theta_A - C.(\dot{\theta}_p - \dot{\theta}_A) - K_p.(\theta_p - \theta_A) = -(F_1 - F_2)R_A \quad (2)$$

$$J_B.\ddot{\theta}_B + C.(\dot{\theta}_B - \dot{\theta}_1) + K_a.(\theta_B - \theta_1) = (F_1 - F_2)R_B \quad (3)$$

$$J_1.\ddot{\theta}_1 + C.\dot{\theta}_1 + K_a.\theta_1 - C.(\dot{\theta}_B - \dot{\theta}_1) - K_a.(\theta_B - \theta_1) = -F_{21}R_1 \quad (4)$$

$$J_{23}.\ddot{\theta}_3 + 2.C.\dot{\theta}_3 + 2.K_b.\theta_3 = F_{12}R_2 - F_{43}R_3 \quad (5)$$

If the motion of a pendulum is clockwise (CW), the gear 4 transmits the motion to the gear 5 and gear 9, while the

gear 6, 7, and 8 are in idle position. The motion equation for gear 4, 5, and 6 are presented below:

$$J_4.\ddot{\theta}_4 + K_C.\theta_4 + K_C.(\theta_4 - \theta_5) = F_{34}R_4 \quad (6)$$

$$J_5.\ddot{\theta}_5 + C.\dot{\theta}_5 + K_C.\theta_5 - K_C.(\theta_4 - \theta_5) = F_{59}R_5 \quad (7)$$

$$J_9.\ddot{\theta}_9 + C.\dot{\theta}_9 + K_{d3}.\theta_9 + C.(\theta_9 - \theta_G) + (K_{d1} + K_{d2}).(\theta_9 - \theta_G) = -F_{59}R_9 \quad (8)$$

From eq. (2) – (8) and from the relations of each gear of $R_A\theta_A = R_B\theta_B$; $R_1\theta_1 = R_2\theta_3$; $R_3\theta_3 = R_4\theta_4$; $\frac{R_1}{R_2} \cdot \frac{R_3}{R_4} \theta_1 =$

θ_4 ; $R_5\theta_5 = R_9\theta_9$ the equation can be rewritten by:

$$\left(J_A + \left(\frac{R_A}{R_B}\right)^2 J_B\right).\ddot{\theta}_A + C.\dot{\theta}_A + K_p.\theta_A + \left(\frac{R_A}{R_B}\right)^2.C.\dot{\theta}_A + \left(\frac{R_A}{R_B}\right)^2.K_a.\theta_A + C.(\dot{\theta}_p - \dot{\theta}_A) - K_p.(\theta_p - \theta_A) - \frac{R_A}{R_B}.C.\dot{\theta}_1 - \frac{R_A}{R_B}.K_a.\theta_1 = 0 \quad (9)$$

$$\left[J_1 + \left(\frac{R_1}{R_2}\right)^2 J_{23} + \left(\frac{R_1}{R_2} \cdot \frac{R_3}{R_4}\right)^2 J_4\right].\ddot{\theta}_1 + \left[2.C + 2.\left(\frac{R_1}{R_2}\right)^2.C\right].\dot{\theta}_1 + \left[2.K_a + 2.\left(\frac{R_1}{R_2}\right)^2.K_b + 2.\left(\frac{R_1}{R_2} \cdot \frac{R_3}{R_4}\right)^2.K_C\right].\theta_1 - \frac{R_A}{R_B}.C.\dot{\theta}_A - \frac{R_A}{R_B}.K_a.\theta_A - \frac{R_3}{R_4} \cdot \frac{R_1}{R_2} \cdot \frac{R_9}{R_5}.K_C.\theta_1 = 0 \quad (10)$$

$$\left(J_9 + \left(\frac{R_9}{R_5}\right)^2 J_5\right).\ddot{\theta}_9 + \left(C + \left(\frac{R_9}{R_5}\right)^2.C\right).\dot{\theta}_9 + \left(K_{d3} + 2.\left(\frac{R_9}{R_5}\right)^2.K_C\right).\theta_9 + C.(\dot{\theta}_9 - \dot{\theta}_G) + (K_{d1} + K_{d2}).(\theta_9 - \theta_G) - \frac{R_1}{R_3} \cdot \frac{R_3}{R_4} \cdot \frac{R_9}{R_5}.K_C.\theta_1 = 0 \quad (11)$$

The mechanical equation for the generator which its input is in clockwise motion is:

$$J_G.\ddot{\theta}_G + B.\dot{\theta}_G + T_e = C.(\dot{\theta}_9 - \dot{\theta}_G) + (K_{d1} + K_{d2}).(\theta_9 - \theta_G) \quad (12)$$

In case that the pendulum rotates counterclockwise, the gear 6 receives the motion from gear 4 and transmits it to the gear 7, then to the gear 8. In order, the equations are:

$$J_4.\ddot{\theta}_4 + K_C.\theta_4 + K_C.(\theta_4 - \theta_6) = F_{34}R_4 \quad (13)$$

$$J_6.\ddot{\theta}_6 + C.\dot{\theta}_6 + K_C.\theta_6 - K_C.(\theta_4 - \theta_6) = -F_{76}R_6 \quad (14)$$

$$J_7.\ddot{\theta}_7 + 2C.\dot{\theta}_7 + 2K\theta_7 = F_{67}R_7 + F_{87}R_7 \quad (15)$$

$$J_8.\ddot{\theta}_8 + C.(\dot{\theta}_8 - \dot{\theta}_G) + K_{d2}.\theta_8 + K_{d1}.(\theta_8 - \theta_G) = F_{78}R_8 \quad (16)$$

By substituting the eq.(13) to eq.(5) and eq.(14)-(15) to eq.(16), then by using the relations between each gear $(\theta_7 = \frac{R_6}{R_7}\theta_6; \theta_7 = \frac{R_8}{R_7}\theta_8)$ leads to the new equations:

$$\left[J_1 + \left(\frac{R_1}{R_2}\right)^2 J_{23} + \left(\frac{R_1}{R_2} \cdot \frac{R_3}{R_4}\right)^2 J_4 \right] \cdot \ddot{\theta}_1 + \left[2.C + 2 \cdot \left(\frac{R_1}{R_2}\right)^2 .C \right] \cdot \dot{\theta}_1 + \left[2.K_a + 2 \left(\frac{R_1}{R_2}\right)^2 K_b + 2 \cdot \left(\frac{R_1}{R_2} \cdot \frac{R_3}{R_4}\right)^2 K_C \right] \cdot \theta_1 - \frac{R_A}{R_B} .C.\dot{\theta}_A - \frac{R_A}{R_B} .K_a.\theta_A - \frac{R_3}{R_4} \cdot \frac{R_1}{R_2} \cdot \frac{R_8}{R_6} K_C \theta_8 = 0 \quad (17)$$

$$\left(J_8 + \left(\frac{R_8}{R_7}\right)^2 J_7 + \left(\frac{R_8}{R_6}\right)^2 J_6 \right) \cdot \ddot{\theta}_8 + \left(C + 2 \left(\frac{R_8}{R_7}\right)^2 .C + 2 \left(\frac{R_8}{R_6}\right)^2 .C \right) \cdot \dot{\theta}_8 + \left(K_{d1} + K_{d2} + 2 \left(\frac{R_8}{R_7}\right)^2 K + 2 \cdot \left(\frac{R_8}{R_6}\right)^2 K_C \right) \cdot \theta_8 - C.\dot{\theta}_G - K_{d1}.(\theta_G) - \frac{R_1}{R_2} \cdot \frac{R_3}{R_4} \cdot \frac{R_8}{R_6} K_C \cdot \theta_1 = 0 \quad (18)$$

While the equation of the generator when the pendulum rotates CCW is:

$$J_G.\ddot{\theta}_8 + B.\dot{\theta}_G + T_e = C.(\dot{\theta}_8 - \dot{\theta}_G) + K_{d1}.(\theta_8 - \theta_G) \quad (19)$$

The electrical equation of the generator is:

$$L \frac{di}{dt} + R.i + e_o = K.\theta_G \quad (20)$$

It can be examined that some of the parameter written on the equation of motion was the mass of pendulum and the arm of the pendulum. In order that the variations used in this study were the mass and the arm of the pendulum. The mass of pendulum was varied from 0,25 kg to

0,75 kg with an interval of 0,25 kg. While, the variation of the pendulum's arm was 100 mm, 150 mm, and 200 mm. The effect of wave amplitude to the power generated by the system was analyzed too.

Table 1. Symbols

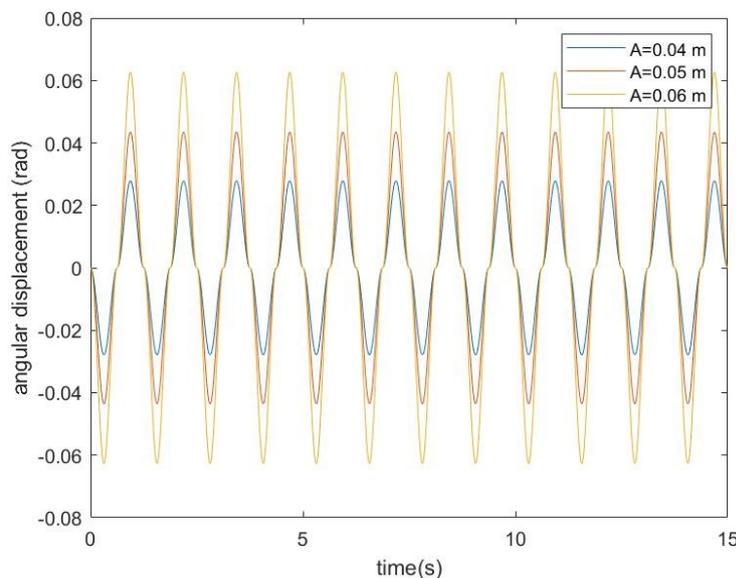
M_p	The mass of the pendulum
M_b	The mass of pendulum's arm
L	The length of pendulum's arm
C	The damping constant of bearing
K_p	The stiffness constant of 1 st shaft
K_a	The stiffness constant of 2 nd shaft
K_b	The stiffness constant of 3 rd shaft
K_{C1}	The stiffness constant of 4 th shaft
K_{d1}	The stiffness constant of 5 th shaft
F_{ij}	The contact force of gear
θ_i	The angle/the angular displacement of gear
$\dot{\theta}_i$	The angular velocity of gear
$\ddot{\theta}_i$	The angular acceleration of gear
R_i	The radius of the gear

3. Results and Discussion

The pendulum of the pontoon oscillates due to the motion of the wave. The angular displacement of the pendulum as a response to the wave amplitude is presented in fig. 3. The angular displacement of the pendulum increases as the wave amplitude increases. The result was corresponding well to the equation of harvester's angular displacement in [11]. The positive sign and the negative sign indicate that the motion of the pendulum is reversed and could not fully rotate. While the rotation of the generator's shaft could not rotate in the reversed direction so that the one-way clutch was installed in gear 5 and gear 6. The motion of gears has been described above. The

angular displacement of gear 8 and gear 9 which was the input motion of the generator's shaft is shown in fig.4.

Figure 4a shows the angular displacement of gear 8 which rotated when the pendulum rotated in counterclockwise. While the gear 9 rotated as the pendulum rotated in clockwise. The angular displacement of gear 8 was higher than the angular displacement of gear 9. It due to the differences in the dimension and the arrangement of gear 8 and gear 9. The radius of gear 8 was smaller than the radius of gear 9. The effect of wave amplitude to the angular displacement of gear 8 and gear 9 was the same as the effect to the angular displacement of the pendulum. The increasing of wave amplitude causes the increasing of the angular displacement of gear 8 and gear 9.

**Figure 3.** The angular displacement of the pendulum

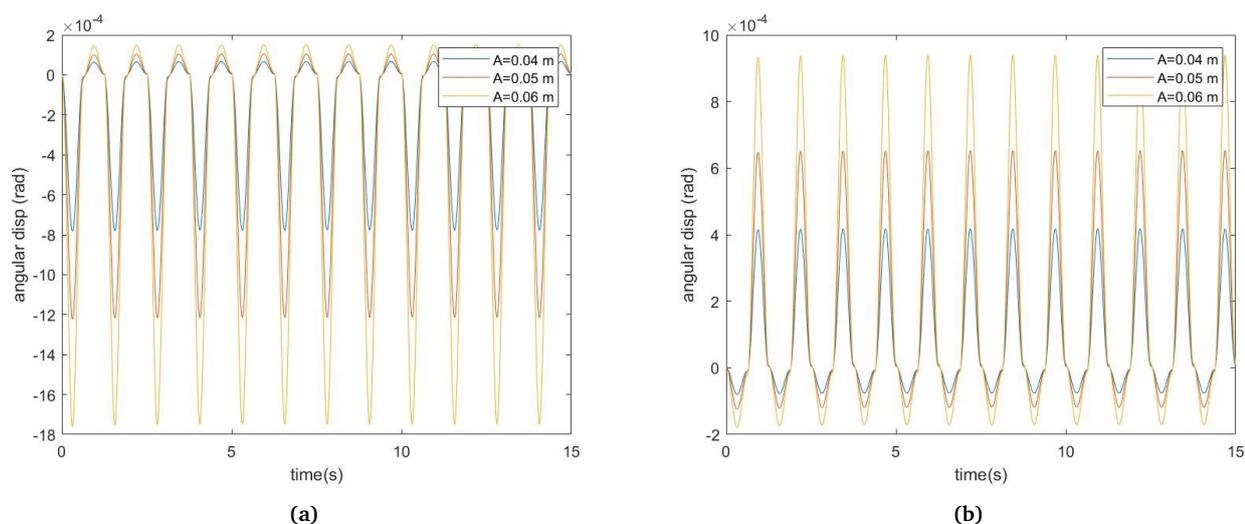


Figure 4. The angular displacement of (a) gear 8, and (b) gear 9

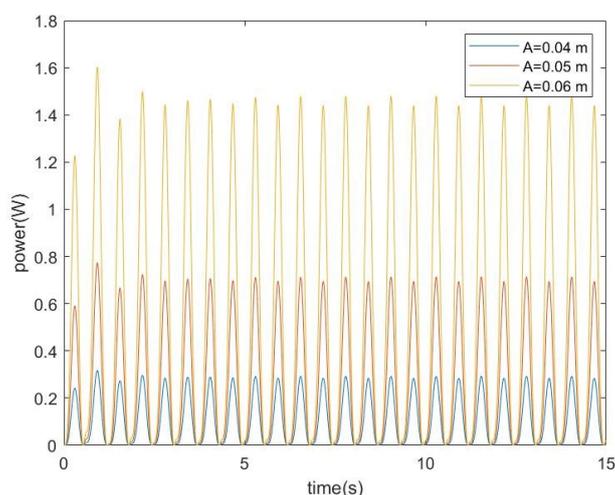


Figure 5. The generated power of SVPM in wave amplitude variation

Then, the generated power of SVPM is presented in fig. 5. The oscillation on the graph indicates that the input motion to the generator was a sinusoidal function instead of step function which correlates to the wave motion. The unsteady peak on the graph was caused by the alternation of the gear 8 and gear 9 motion which was the input of the generator's shaft. The zero-value of the generated power implies the motion of the pendulum which has zero-velocity at the maximum displacement from its equilibrium position. The increasing of wave amplitude causes the increment of angular displacement of the pendulum which enhances the angular displacement of gear 8 and gear 9, then escalates the generated power.

Figure 6 established the effect of the length of the pendulum to the RMS of SVPM generated power. The graph of power generated to the increasing of the pendulum length has the same trend line in each wave amplitude. It can be observed that the increment of generated power

of SVPM is proportional to the increment of the length of the pendulum. However, the relation between generated power and the length of the pendulum is not linear. The effect of pendulum mass to the generated power of SVPM similar to the effect of pendulum length. The heavier of the pendulum mass enlarges the angular displacement of the pendulum which leads to the increment of power that can be generated by SVPM.

The discussion about the effect of wave amplitude has been discussed above. Figure 7 declares the quantitative data of the generated power in the variation of wave amplitude. The highest generated power was 0,75 Watt occurred when the wave amplitude is 0,06 m. The effect of the wave amplitude was dominant compared to the effect of the pendulum length. The differences in generated power in the variation of pendulum length was slight and almost form a step trend line.

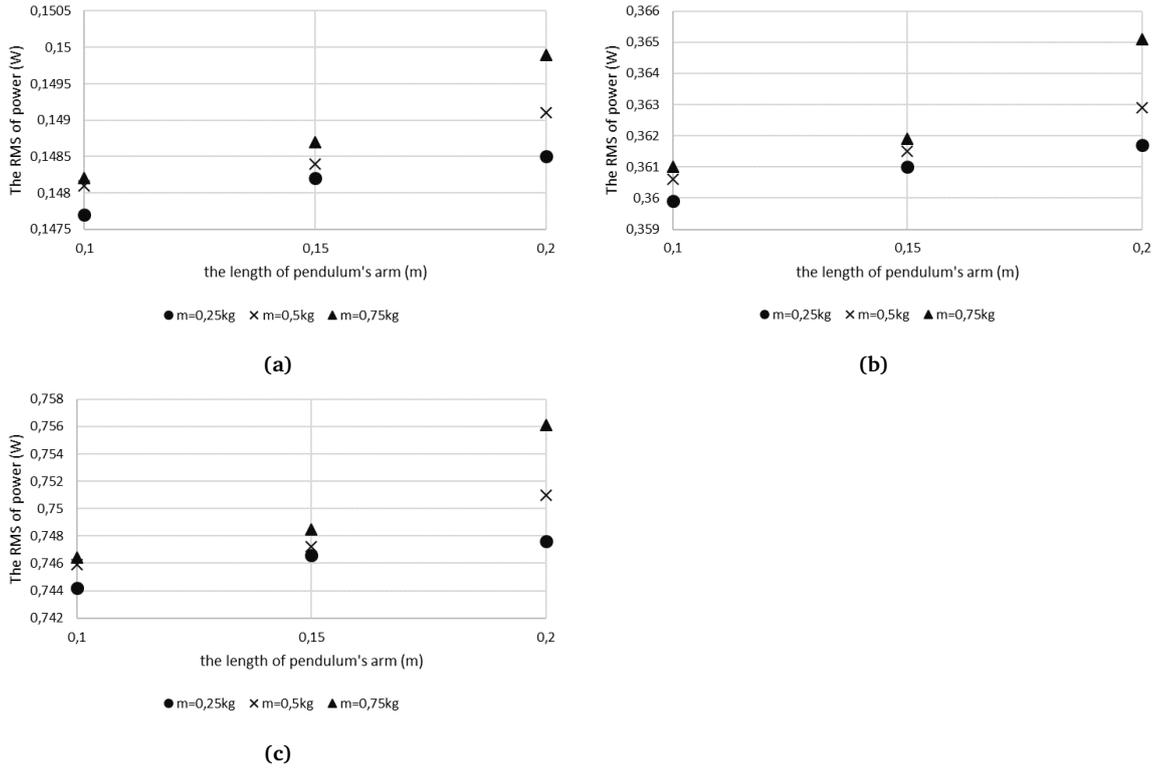


Figure 6. The RMS of generated power in mass variations vs the length of pendulum, (a) Wave amplitude (A) = 0,04 m, (b) A = 0,05 m, and (c) A = 0,06 m

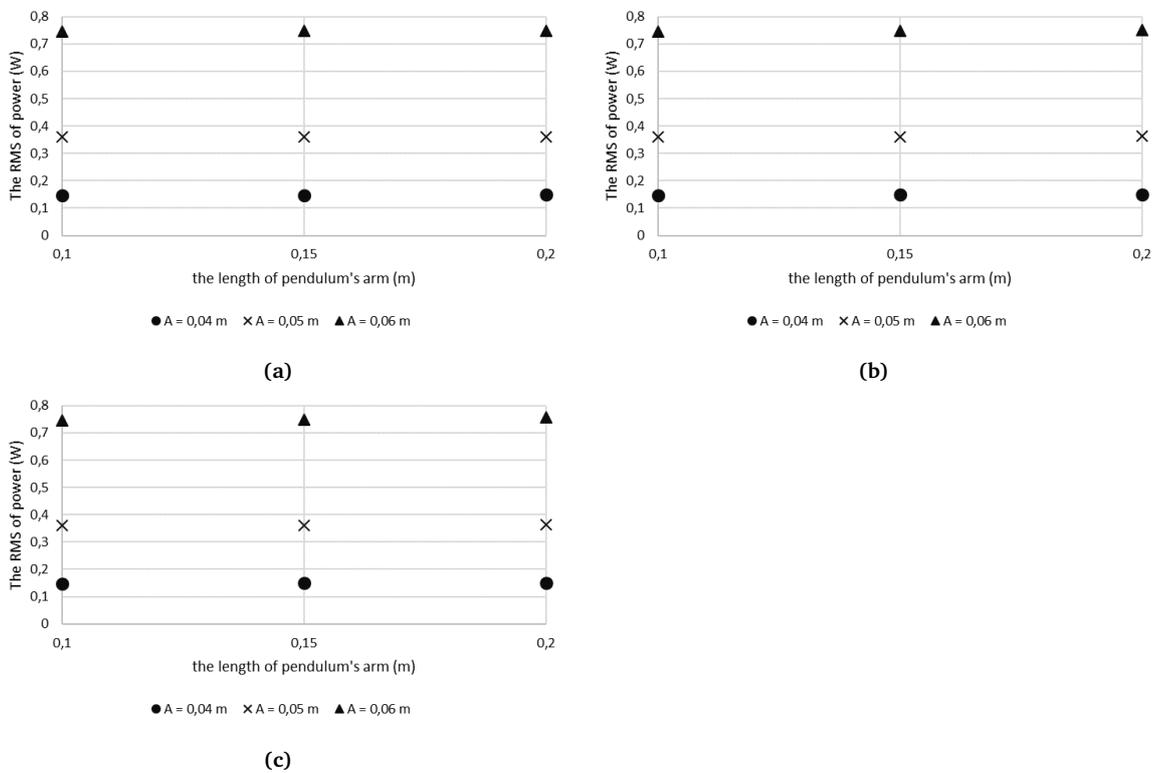


Figure 7. The RMS of generated power in wave amplitude variations vs the length of pendulum, (a) pendulum mass (m) = 0,25 kg, (b) m = 0,5 kg, and (c) m = 0,75 kg

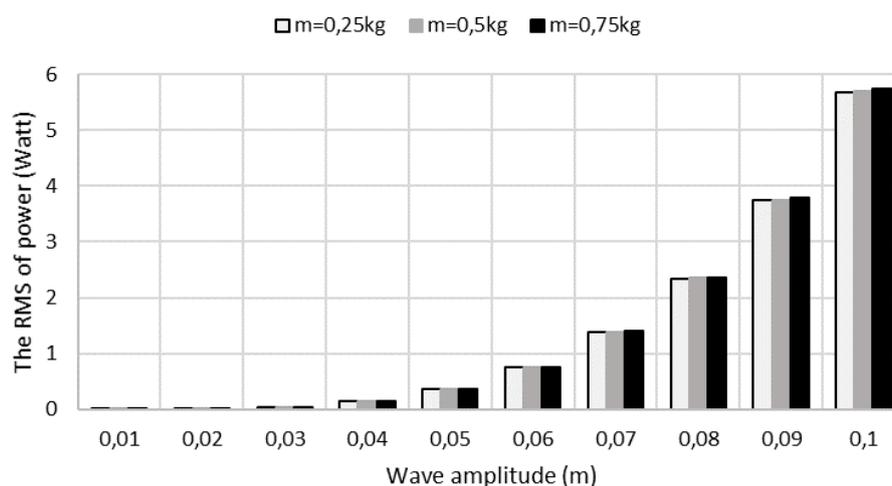


Figure 8. The effect of wave amplitude and the pendulum mass to the RMS of generated power

Figure 8 presents more generated power's data which the wave amplitude variations are from 0,01 m to 0,1 m with an interval of 0,01 m. It provides the effect of the pendulum mass and the effect of the wave amplitude to the generated power more clearly. The effect of the pendulum mass is detectable in the higher wave amplitude. While the effect of the wave amplitude to the generated power is observable from low wave amplitude.

4. Conclusions

It can be concluded that the design of SVPM could generate the maximum electrical power of 0,75 Watt which occurred at the wave amplitude of 0,06 m, the pendulum length of 0,2 m, and the pendulum mass of 0,75 kg. The pendulum length and the pendulum mass give a slight effect on the generated power of SVPM. While the wave amplitude affects more dominant to the generated power of SVPM. As stated above, the dimension of the mechanism and the wave amplitude were on a laboratory scale. The generated power may be higher if it applied on a real scale with the real ocean wave amplitude which is approximately 0,1 m to 1,2 m. Furthermore, the simulation's results could be compared to the experimental result in later study.

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