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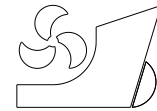*Ridho Hantoro*
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STABILITY ANALYSIS FOR TRIMARAN PONTOON ARRAY IN WAVE ENERGY CONVERTER – PENDULUM SYSTEM (WEC - PS)

Summary

Ocean waves are a renewable energy source with abundant reserves in Indonesia. With the vast waters of Indonesia, the development of a sea wave power plant needs to be developed. This research focuses on the development of easy-operated and maintained ocean wave converter–pendulum system (OWC – PS). The numerical simulation and experimental analysis were conducted to obtain the relation between the motion response of the pontoon array and its pendulum. The pontoon used is the trimaran type, which consists of a cylindrical pontoon as the main hull and two outriggers on its side. This study analyses the most stable array arrangement that produces maximum pitching motion and pendulum deviation. The simulation results show that the largest pitching value is in array 1, i.e., 27.91° for pontoon 1 and 38.92° for pontoon 2, which results in a maximum pendulum deviation of 100 ° for pendulums 1 and 56.2 ° for pendulum 2 over a wave period of 9 seconds. The backward motion of the pendulum in both array configurations tends to have a greater deviation than that of the forward motion. The pendulums of array 1 have different motion characteristics, represented by different deviation values in both pendulums. This phenomenon does not occur in array 2, since both pendulums in array 2 have the same deviation (with only a small discrepancy).

Keywords: Array; Pendulum; Pontoon; Trimaran; WEC

1. Introduction

A study conducted by the Indonesian Energy Association (ASELI) in 2012 indicates that Indonesia has 1.2 GW ocean wave potential [1], which makes it attractive to be developed as alternative energy. Implementing ocean wave energy converter (WEC) technology seems to be the solution for the rural island [2]. For rural applications, WEC should be easily operated and maintained [3]. Besides the power generation, the WEC can be considered a wave breaker [4].

Wave energy has a high availability factor compared with other resources, resource predictability, high power density, and low environmental and visual impact [5]. Hence the development of wave energy is still massive [6]. Commonly, wave energy technology is divided into three types, namely: oscillating water columns, oscillating bodies, and overtopping systems, which can be fixed, floating, or submerged structures [7]. Several system models have been proposed, including oscillating water column (OWC) [8], single-body heaving buoys [9]–[11], two-body heaving buoys [12], [13], full submerge heaving system, pitching device, bottom-hinged system and many-body system [7]. Several WEC technologies have been

developed, i.e. Wave Dragon, Pelamis, Aqua Buoy, Archimedes Wave Swing, Langlee, Oceantec, OE Buoy, Pontoon, Seabased AB, Wavebob and SSG [14].

One of the most applicable wave energy converters is based on pendulum technology combining with pontoon system, considered a simple concept [15], [16]. The pendulum system is coupled to the mechanical transmission and generator to produce electricity. The power generated is highly influenced by the pitching angle and period of the pendulum and the pontoon system used as a pendulum support structure. Arief et al. [17] state that the pontoon with a 2/3 cylinder diameter gives the best performance while installed for the WEC system. The rolling stability of the pontoon can be analyse using two approaches, i.e., deterministic methods and stochastic methods. The current study uses deterministic methods, which employs regular wave with constant system coefficient [18].

The power gained by the WEC-pendulum system (WRC-PS) can be enhanced by several methods, including choosing the suitable site, using the multi-pendulum system, or using an array system. WEC-PS will produce high power when installed in the deep-water [19], [20]. However, the O&M will be an important issue as it requires complex procedures and high operation and maintenance costs. The multi-pendulum pontoon is the other alternative to increase the power extraction of WEC-PS, but the pendulums move at a smaller deviation angle [21]. Hence it needs a more complex mechanical system to meet the generator requirement. Installing WEC-PS in array configuration seems to be a promising technology to improve performance. The wave energy extracted by WEC-PS in an array advances its performance compared to the single system [22], [23]. Using an array system, each WEC-PS is fabricated in a small capacity and installed in several pieces (modules) according to the designed generating capacity.
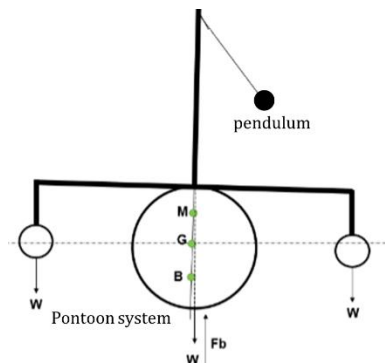

Fig. 1 Schematic of WEC-PS

This study conducted an experiment and simulation to analyse the WEC-system pontoon array, aiming to get the high deviation pendulum and pontoon installed in the array system. The novelty of this work is the relation between the motion response of the cylindrical trimaran pontoon array and its pendulum. This work contributes to the consideration of pontoon array design, especially in applying WEC-PS.

2. Methods

2.1 System design and configuration

The schematic of the WEC-PS system is depicted in Figure 1. It generally embodies 2 main parts called the WEC-PS module, consisting of the pendulum and trimaran pontoon systems. The former is responsible for generating torque to the shaft. Meanwhile, the latter is the pendulum's support, which takes an important role in converting energy from the wave to the pendulum system. Two modules are arranged in the array configuration to analyse the effect of this arrangement on the pitching of the pontoon and pendulum. Two array configurations

were designed and analysed, including front-rear (array 1) and side-by-side configuration (array 2), as shown in Figure 2 and Figure 3. The Computational Fluid Dynamics (CFD) simulation and experimental study on towing tank are conducted to examine both configurations.

2.2 Simulation Setup

The simulation is conducted in two steps, namely: pontoon simulation, which provides pontoon motion, and pendulum simulation. The pontoon response data from the first step is used in the pendulum simulation to secure the pendulum response. The model simulated is the same size as the prototype design, which has 3.2 m of pontoon length, 0.4 m of pontoon diameter, and 410 kg of pendulum system.
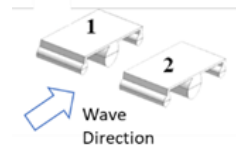

Fig. 1 Front-rear (array 1)   **Fig. 2** Side-by-side (array 2)

At the first simulation step, pontoon simulation, the model is meshed with a total element number of 34,198. The model is assumed to be connected by a liner cable with the stiffness of 1 N/m. The "regular wave response" analysis type is employed, and the wave direction is from the front. This condition produces greater pendulum deviation since the incoming wave is in the direction of pendulum deviation. The wave period is varied to be 7, 8, and 9 seconds. The pontoon response is obtained from the pendulum simulation, which is used in the next step of the simulation.

The pendulum simulation is started using rigid dynamic simulation. It will show the phenomenon of pendulum motions as the effect of pontoon motions. The grid generation was carried out using Quad/Tri (Multizone) method. The joint between the pendulum and pontoon is assumed to be a cylindrical joint.
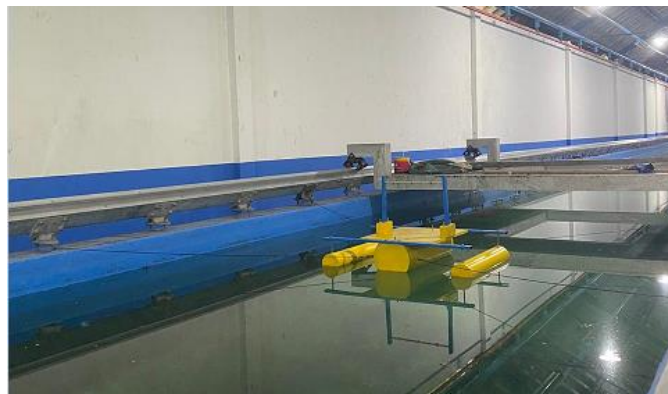

Fig. 4 Experiment WEC-PS

2.3 Experimental Setup

The prototype with a scale of 1:1 in the simulation is modelled with a dynamic similarity approach for the parameters of gravity and inertia forces, following the Froude Number (Fr) equality of the magnitude ratio of gravity to inertia force at the corresponding points in the system. The model has Froude Number of 0.17. Hence the model will have 0.6 m in length and the wave period is 0.2 s.

Experiments were carried out at a towing tank facility in the ITS hydrodynamics laboratory rather than an offshore basin. This is because the towing tank provides smooth flow

inlet conditions and avoids the uncertain impact of inlet current turbulence. The dimension of the towing tank is 50 m in length, 3 m in width, and 2 m in depth. The experimental setup is given in Figure 4; meanwhile, the deviation is measured using arc, as shown in Figure 5. The pithing angle of pontoon and pendulum is measured using an arc embodied in the WEC-PS model. The wave generated by the wave generator in the towing tank needs several seconds to get into its set point. Hence the data had been collected when the array system reached its steady condition. The array models were subjected to three wave periods with the same amplitude of 0.1 m, i.e., 0.2 s, 0.23 s, and 0.26 s.

Fig. 5 Deviation measurement

The experimental results are employed for checking the data validity in the simulation process. Validation was carried out by comparing the deviation obtained from the simulation with the experimental data for each array. The difference between experimental and simulation results for Array 1 is approximately 16%, while only 5% for Array 2.

3. Results and Discussion

3.1 CFD Simulation Result

The pitching motion is an up and down movement of the pontoon due to the force of the regular incoming waves. The analysis concentrates on the pitching motion of pontoon and pendulum. Figure 4 shows the pitching motion of array 1. The pitching motion (RX) of both pontoon 1 and pontoon 2 has the largest deviation for wave with a period of 9s, followed by the second largest at 8s and finally at 7s. As the wave is generated in zero amplitude until it reaches the set point at several seconds, Figures 6 and Figure 7 depict that the simulation needs approximately 12 seconds to reach its steady condition.
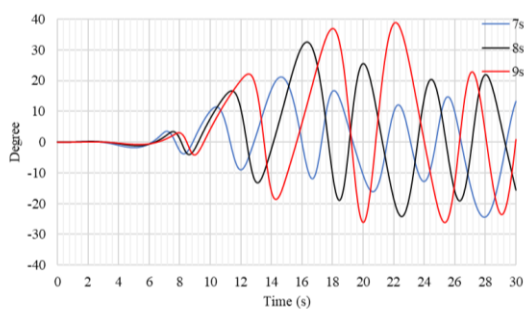

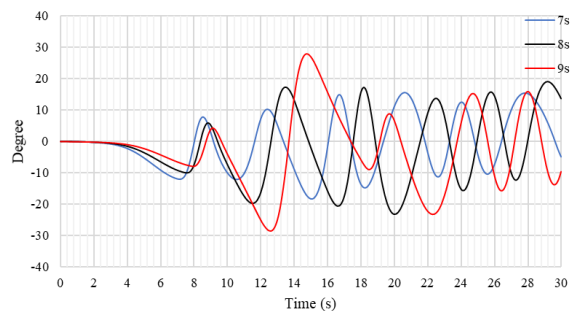**Fig. 6** Pitching motion of array 1 for pontoon 1   **Fig. 7** Pitching motion of array 1 for pontoon 2

The oscillatory movement on pontoon 1 starts with an ascending (constructive) graph while pontoon 2 starts with a descending (destructive) movement first. This is due to the incoming waves from the front which act the body and lift the pontoon 1 and give weight to the pontoon 2 to sink slightly due to the cable connection. The pitching motion on pontoon 1 has a relatively greater average value than pitching on pontoon 2, in all wave period variations. The 9s period has the largest pitching deviation due to pontoon 1 and pontoon 2 will receive a wave every 9 seconds so that the 1st and 2nd pontoon bodies have longer time to oscillate maximally, compared to the 8s and 7s periods which have less potential for the pontoon to find the maximum oscillation as the first wave arrives, causing the reversing force of the pitching motion, which suppresses motion rotation.
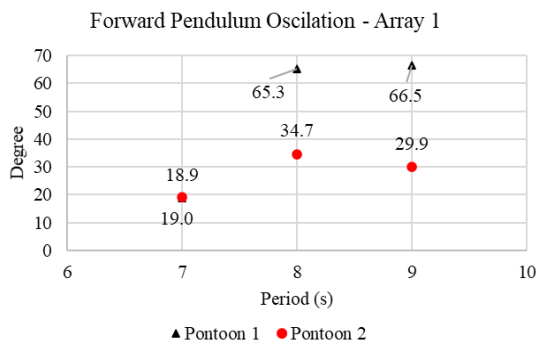

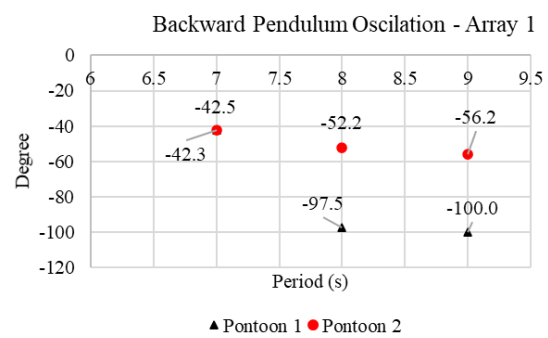Fig. 8 Maximum forward deviation of pendulum in Array 1

Fig. 9 Maximum backward deviation of pendulum in Array 1

Figure 8 and Figure 9 exhibit the response of pendulum of array 1. The pendulum deviation in array 1 has the greatest value during the greatest period (9s) both on pontoon 1 and on pontoon 2. This simulation result shows that both pendulums do not give the same response. The pendulum in pontoon 1 tends to have almost two times greater deviation than pendulum in pontoon 2.
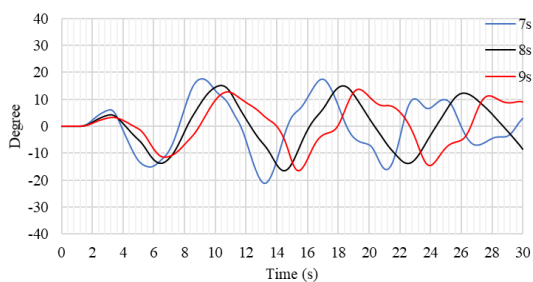

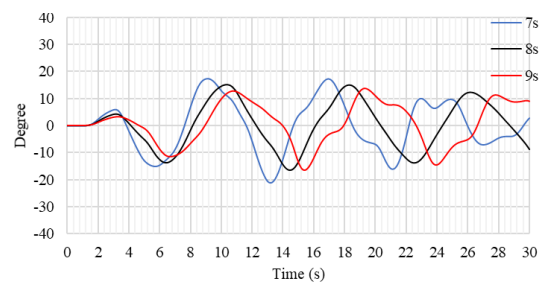Fig. 10 Pitching motion of array 2 for pontoon 1

Fig. 11 Pitching motion of array 2 for pontoon 2

For Array 2, the pitching motion (up and down) had an almost identical movement tendency between pontoon 1 and pontoon 2 due to the position when the incoming waves of the two pontoon bodies were on the same axis or parallel. Thus, the incoming wave radiation will be the same on pontoon 1 and 2. However, the maximum pitching angle of array 2 is only 3 degrees. Figure 10 dan Figure 11 also depict that the greater pontoon pitching angle occurs at a wave period of 7 seconds, slightly different from Array 1. It shows that the wave interaction affect the pontoon's oscillating motion. It can be constructive or destructive depending on the wave period. This phenomenon is in accordance with research conducted

by [24]. The forward deviation of pendulum is smaller than its backward deviation. The pontoon is lifted backward and tends to maintain that position so that the large pendulum moves towards the back.
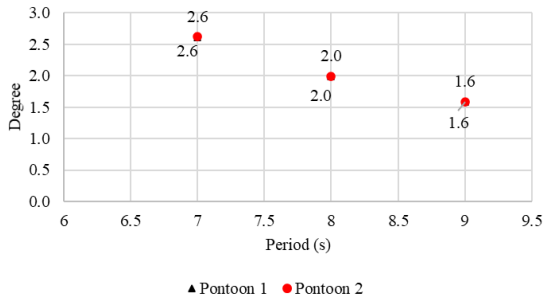

Fig. 12 Maximum forward deviation of pendulum in Array 2
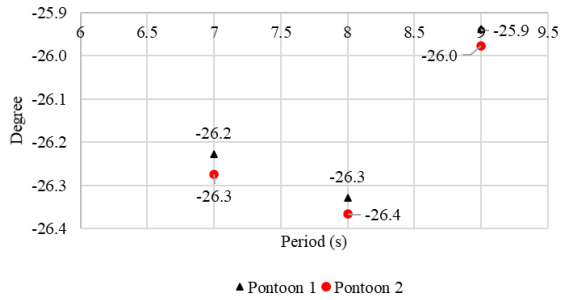

Fig. 13 Maximum backward deviation of pendulum in Array 2

3.2 Experimental Result

In general, each array has different pitching characteristics. The pontoon pitching response produces a response that forms a sinusoidal pattern. In pontoon 1, the increasing wave period causes the increase of the pitching angle of the pontoon, as the simulation result. However, the increase of the wave period results in a low-frequency pitching response. In contrast to pontoon 1, changing the wave period causes a slight increase in the pitching angle of pontoon 2, as shown in Figure 14 dan Figure 15.
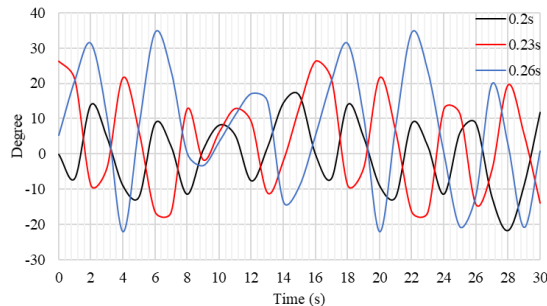

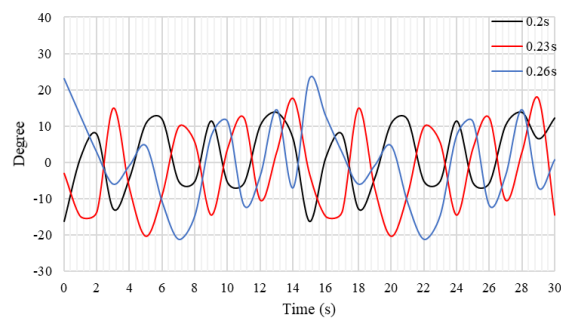**Fig. 14** Experimental Pitching motion of array 1 (Pontoon 1)

Fig. 15 Experimental Pitching motion of array 1 (Pontoon 2)

The characteristics of the pontoon response affect the pendulum response, as shown in Figure 16 and Figure 17. In general, the increase in the wave period improves the pendulum deviation. In the 8s and 9s periods, the pendulum on pontoon 1 tends to have a larger deviation than the pendulum on pontoon 2. Meanwhile, the maximum deviation occurs when the pendulum moves backward.

The experimental results state that the responses of pontoon 1 and pontoon 2 in array 2 have the same characteristics, as shown in Figure 18 and Figure 19. As the pontoon is set side-by-side, both pontoons are subjected to the same undisturbed wave. In other words, the presence of pontoon 1 does not influence the wave received by pontoon 2, and vice versa. Thus, the responses for the two pontoons are similar. The wave period does not cause a significant increase in the pitching angle for both pontoons. Figure 18 and Figure 19 show that both pontoons have almost the same pitching angle for each variation of the wave period.
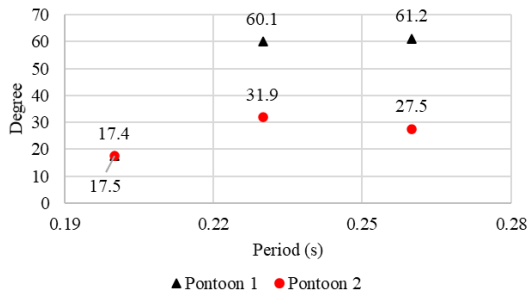
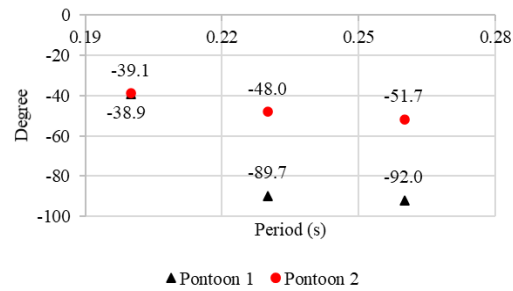**Fig. 16** Maximum forward deviation of experiment pendulum in Array 1

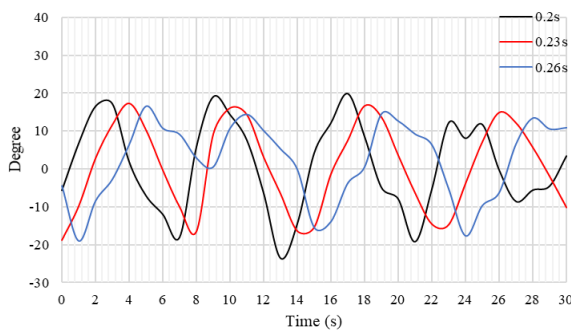**Fig. 17** Maximum backward deviation of experiment pendulum in Array 1

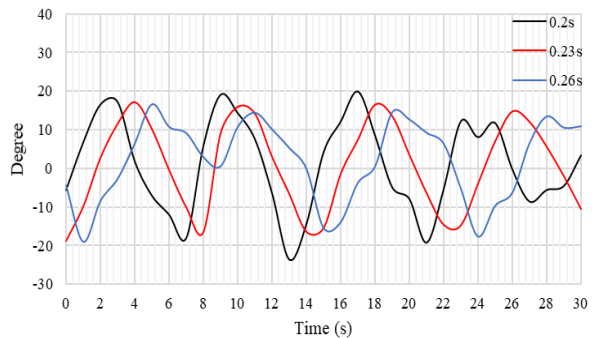**Fig. 18** Experimental Pitching motion of array 2 for pontoon 1

Fig. 19 Experimental Pitching motion of array 2 for pontoon 2

In array 2, due to the identical response of the pontoons, the pendulum response in pontoon 1 is the same as the pendulum response in pontoon 2, especially for forward motion. Meanwhile, there is a slight difference in the pendulum deviation for backward motion, as shown in Figure 20 and Figure 21. Backward motion produces a larger deviation than that of the forward motion. The variation of the wave period does not result in a significant increase in pendulum deviation, approximately 25° of deviation, which occurs during backward motion. Meanwhile, an increase in period causes a decrease in the pendulum deviation during the forward motion.

3.3 Discussion

The criteria for the best array arrangement are obtained from pitching motion which produces maximum deviation in the pendulum but still maintains the balance of pontoons. Based on the experimental and simulation result, the pitching motion of array 1 is large enough. Whereas in array 2, the pitching motion has a small deviation, which is approximately 10° on average in all periods, as shown in Figure 20 (based on the experimental result). This small intersection produces a small pendulum deviation. It is in accordance with [25], which suggests not to choose the square-based array as a strong masking effect probably occurs, especially for short separating distances .

Meanwhile, the constructive effect occurs in triangle-based configuration (between the front and rear configuration), which also arises in array 1 (front-rear configuration). The phenomenon in the Array 1 also agrees with the research conducted by [26] which shows that the shadow zone of low wave amplitude between the front pontoon and the rear pontoon has been enhanced due to the motion of the front pontoon. Hence, the array 1 gains more power, indicated by higher pitching angle.
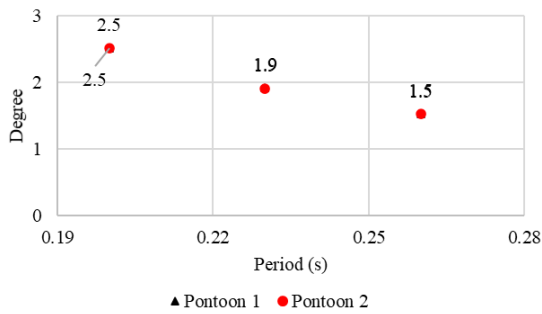
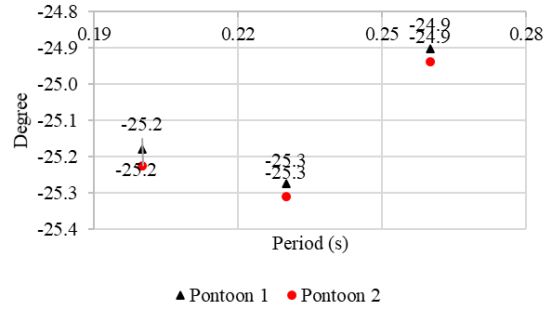**Fig. 20** Maximum forward deviation of experiment pendulum in Array 2

Fig. 21 Maximum backward deviation of experiment pendulum in Array 2

Meanwhile, array 1 can achieve a pitching angle of 12.4˚. The front – rear arrangement of array 1 increases the pitching angle of pontoon, especially for pontoon 1 (front pontoon). The array 1 has the most stable pitching motion at pontoon 1 and 2. The experimental and simulation result of array 1 is in accordance with the research conducted by [16], which shows that the pontoon's pitching angle and pendulum deviation is raised in consort with the wave period.
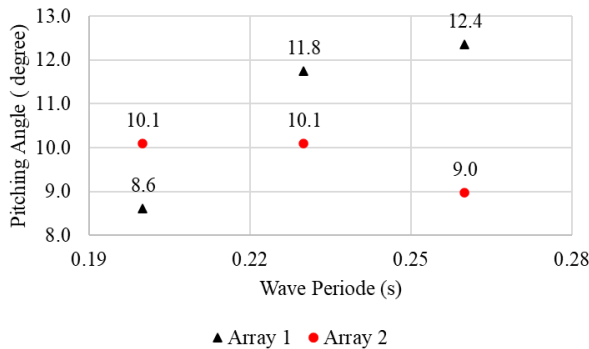

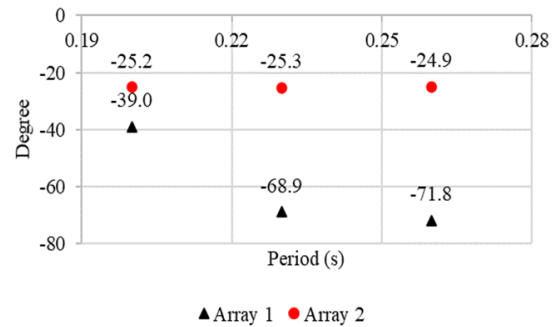**Fig. 20** Deviation of pontoon

Fig. 21 Deviation of pendulum

Due to the larger pitching angle in array 1, the pendulums gain maximum deviation, as shown in Figure 21. The negative sign in Figure 21 indicates that the large deviation is dominated by backward pendulum movement. As the pendulum moves forward, the pendulum tends to have a smaller deviation. This happens because the pendulum is positioned parallel to the wave's propagation direction. Hence, the pendulum moves forward while the wave moves backward, producing a smaller relative force and inhibiting the pendulum movement.

The current study only compares the performance of array 1 and array 2 configurations. Based on the study, array 1 is recommended since it produces greater pendulum deviation compared to array 2. Implementing multiple arrays is possible, and the development should consider the characteristics of array 1 and 2.

4. Conclusion

Two pontoon configurations were simulated and tested: front-rear configuration (array 1) and side-by-side configuration (array 2). Both configurations were simulated in wave periods of 0.7 s, 0.8 s and 0.9 s, which is appropriate for wave characteristics in Indonesia.

Meanwhile, the dynamic similarity approach using Froude Number (Fr) was employed to get the experimental parameter. The study shows that differences in array arrangement and wave period affect pitching angle of pontoon. Array 1 and array 2 have different characteristics of dominant motion. In array 1, the pitching value increases with the periods, in which the largest value is at a wave period of 9 seconds. Array 1 can achieve a pitching angle of 12.4 degrees. Meanwhile, pontoon in array 2 has smaller pitching angle. The effect of wave period on pitching motion is not significant in array 2. Moreover, in array 1, the front pontoon has good impact on the rear pontoon, as it can enhance the low amplitude zone between pontoons. The pontoon movement directly affects the deviation of pendulum. Based on the simulation result, the pendulum in array 1 deviates better than array 2 with a maximum deviation of 100 degrees on pendulum 1 and 56.2 degrees on pendulum 2. The backward motion of the pendulum tends to have a greater deviation than that of the forward motion since it is in the same direction of wave propagation.

Acknowledgement

REFERENCES

[1]   Baidowi, A., Semin, S., Koenhardono, E. S., Amiadji, A., Ainin, F., 2019. Motion Response of a Novel Platform of Vertical Axis Marine Current Turbine, *International Review of Mechanical Engineering*, 13(12), 710. https://doi.org/10.15866/ireme.v13i12.18035

[2]   Ma, Z., 2018. Solutions for Remote Island Microgrids : Discussion and analysis of Indonesia's remote island energy system. *International Conference on Innovative Smart Grid Technologies*, ISGT Asia. https://doi.org/10.1109/ISGT-Asia.2018.8467954

[3]   Rusu, E., 2014. Evaluation of the Wave Energy Conversion Efficiency in Various Coastal Environments. *Energies*, 7(6), 4002–4018. https://doi.org/10.3390/en7064002

[4]   Ruol, P., Zanuttigh, B., Martinelli, L., Kofoed, P., Frigaard, P., 2011. Near-Shore Floating Wave Energy Converters: Applications For Coastal Protection. *Coastal Engineering Proceedings*, 1(32), 61. https://doi.org/10.9753/icce.v32.structures.61

[5]   Chuah, E., Magaswaran, K., Hassan, M. Z., 2017. Design and Modelling of Wave Energy Converter and Power Take-off System. *The International Journal of Advanced Manufacturing Technology*, 12(12), 209 - 222.

[6]   Janzen, F. C., Tusset, A. M., Balthazar, J. M., Rocha, R. T., de Lima, J. J., Nabarrete, A., 2019. Offshore energy harvesting of a marine floating pendulum platform model. *Latin American Journal of Solids and Structures*, 16(1), 1-13. https://doi.org/10.1590/1679-78255006

[7]   Falcão, A. F. d. O., 2010. Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3), 899–918. https://doi.org/10.1016/j.rser.2009.11.003

[8]   Masuda, T., 1983. Wave-activated power generator. WO1984001603A1

[9]   Budal, K. Falnes, J., Iversen, L.C., Lillebekken, P.M., Oltedal, G., Hals, T., Onshus, T., Arne, S. H., 1982. The Norwegian wave-power buoy project.

[10]   Elwood, D., Schacher, A., Rhinefrank, K., Prudell, J., Yim, S., Amon, E., Brekken, T., von Jouanne, A., 2009. Numerical modeling and ocean testing of a direct-drive wave energy device utilizing a permanent magnet linear generator for power take-off. *International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, 4(B), 817–824. https://doi.org/10.1115/OMAE2009-79146

[11]   Waters, R., Stålberg, M., Danielsson, O., Svensson, O., Gustafsson, S., Strömstedt, E., Eriksson, M., Sundberg, J., Leijon, M., 2007. Experimental results from sea trials of an offshore wave energy system.

Applied physics letters, 90(3), 034105. https://doi.org/10.1063/1.2432168

[12] Beatty, S. J., Buckham, B. J., Wild, P., Frequency Response Tuning For a Two-Body Heaving Wave Energy Converter. *The Eighteenth International Offshore and Polar Engineering Conference*, Vancouver, Canada.

[13] Korde, U. A., 2003. Systems of reactively loaded coupled oscillating bodies in wave energy conversion. *Applied Ocean Research*, 25(2), 79–91. https://doi.org/10.1016/S0141-1187(03)00044-0

[14] Legaz, M. J., Soares, C. G., 2022, Evaluation of Various Wave Energy Converters in the Bay of Cádiz, *Brodogradnja*, 73(1), 57–88. https://doi.org/10.21278/brod73104

[15] Santhosh, N., Baskaran, V., Amarkarthik, A., 2015. A review on front end conversion in ocean wave energy converters. *Frontiers in Energy*, 9(3), 297–310. https://doi.org/10.1007/s11708-015-0370-x

[16] Rinaldi, G., Fontanella A., Sannino G., Bracco G., Giorcelli E., Mattiazzo G., Bludszuweit H., 2016. Development of a simplified analytical model for a passive inertial system solicited by wave motion. *International Journal of Marine Energy*, 13, 45–61. https://doi.org/10.1016/j.ijome.2015.10.003

[17] Arief, I.S., Utama, I.K.A.P., Hantoro, R., Prananda, J., Safitri, Y., Rachmattra, T.A., Rindu, F. K., 2018. Response to Pontoon and Pendulum Motion at Wave Energy Converter Based on Pendulum System. *ASTECHNOVA 2017*, 43, 01022. https://doi.org/10.1051/e3sconf/20184301022

[18] Y. Zhang, P. Wang, Y. Liu, and J. Hu, 2021. Nonlinear rolling stability and chaos research of trimaran vessel with variable lay-outs in regular and irregular waves under wind load, *Brodogradnja*, vol. 72, no. 3, pp. 97–123. https://doi.org/10.21278/brod72307

[19] Cascajo, R., García, E., Quiles, E., Correcher, A., Morant, F., 2019. Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia. *Energies*, 12(5), 787-800. https://doi.org/10.3390/en12050787

[20] Drew, B., Plummer, A. R., Sahinkaya, M. N., 2009. A review of wave energy converter technology. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 223(8), 887–902. https://doi.org/10.1243/09576509JPE782

[21] Utama, I. K. A. P., Hantoro, R., Septyaningrum, E., Khasanah, Q., Prananda, J., Arief, I. S., 2021. Analysis of pontoon multi pendulum motion response trimaran model at ocean wave power plant based on pendulum system (PLTG-SB). *IOP Conference Series: Materials Science and Engineering*, 1052(1), 012063. https://doi.org/10.1088/1757-899X/1052/1/012063

[22] Fang, H. W., Feng, Y. Z., Li, G.P., 2018. Optimization of Wave Energy Converter Arrays by an Improved Differential Evolution Algorithm. *Energies*, 11(12), 3522. https://doi.org/10.3390/en11123522

[23] Kara, F., 2016. Time domain prediction of power absorption from ocean waves with wave energy converter arrays. *Renewable Energy*, 92, 30–46. https://doi.org/10.1016/j.renene.2016.01.088

[24] Babarit, A., 2010. Impact of long separating distances on the energy production of two interacting wave energy converters. *Ocean Engineering*, 37(8-9), 718–729. https://doi.org/10.1016/j.oceaneng.2010.02.002

[25] Borgarino, B., Babarit, A., Ferrant, P., 2012. Impact of wave interactions effects on energy absorption in large arrays of wave energy converters. *Ocean Engineering*, 41, 79–88. https://doi.org/10.1016/j.oceaneng.2011.12.025

[26] Wolgamot, H. A., Taylor, P. H., Taylor, R. E., 2012. The interaction factor and directionality in wave energy arrays. *Ocean Engineering*, 47, 65–73. https://doi.org/10.1016/j.oceaneng.2012.03.017