Arab Institute of Navigation
Cross Road of Sebaei Street& 45 St., Miami, Alexandria, Egypt
Tel: (+203) 5509824
Cell: (+2) 01001610185
Fax: (+203) 5509686
E-mail: ain@aast.edu
Website: www.ainegypt.org

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NUMERICAL ANALYSIS OF WAVE ENERGY POINT ABSORBERS BUOY SHAPE

Prepared By
Mohamed Walid abd Elhamed Ahmed
Arab Academy for Science, Technology and Maritime Transport

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المستخلص:
لقد زاد الطلب على الطاقة بشكل كبير هذه الأيام مما أدى إلى تزايد استهلاك الكهرباء، والتي يتم توفير معظمها عن طريق الوقود الأحفوري، مما أدى إلى زيادة تكاليف الطاقة وكذلك الانبعاثات الضارة الناتجة عن احتراق الوقود. وقد أدى ذلك إلى التقدم في استخدام مصادر الطاقة المتجددة لتلبية الطلب الحالي على الطاقة. وتشمل هذه المصادر استخدام الطاقة الشمسية وطاقة الرياح والأمواج لتوليد الطاقة بطريقة خضراء. يعرض هذا البحث استخدام ممتصات نقاط الطاقة الموجية بأشكال مختلفة لتقييم أدائها عند تعرضها للموجات. تم تصميم أربعة أشكال من العوامات وتحليلها باستخدام برنامج Ansys Aqwa لملاحظة حركتها وكذلك استجابتها للقوى غير المتوازنة التي تتعرض لها. أظهرت النتائج أن العوامة ذات الشكل الأسطواني يمكنها تحقيق حركة أكبر بنسبة ٥٢.٨% في الاتجاه الرأسي مقارنة بمتوسط حركة تصميمات العوامات المختلفة. وهذا يدل على أن العوامة الأسطوانية هي الخيار الاقتصادي لامتصاص طاقة الأمواج بشكل أفضل.

ABSTRACT:
Energy demands have increased dramatically nowadays giving rise to the growing consumption of electricity, most of which is provided by fossil fuels, which has increased energy costs as well as the harmful emissions resulting from fuel combustion. This has resulted in advancements in the use of renewable energy sources to satisfy the current energy demands. These sources include the use of solar, wind, and wave power to generate energy in a green manner. This paper presents the use of wave energy point absorbers with various shapes to assess their performance when exposed to waves. Four buoy shapes are modelled and analyzed using Ansys Aqwa to observe their motion as well as their responsiveness to the out of balance forces subjected on them. The results show that the cylindrically shaped buoy can achieve around 52.8% more motion in the vertical direction when compared to the average motion of the different buoy designs. This shows that a cylinder buoy is the economic option for optimized wave energy absorption.

Keywords: Wave Power, Green Energy, Point absorbers, Numerical Simulation

1. INTRODUCTION

Given the harmful impacts of fossil-based energy sources and the growing consumption of electricity, governments have taken considerable steps towards sustainable development and the application of renewable sources of energy in their various forms such as solar, wind and wave power to reduce environmental pollution (Viet et al., 2016). Among the commonly used renewable sources of solar and wind energy, wave energy has the highest power density and provides the most availability through 90% of the time which increases its reliability when compared to other renewables (Beirão & Malça, 2014). Therefore, great efforts were made to utilize wave energy through various technologies of wave energy converters (WEC) which include point absorbers, oscillating water columns, and overtopping devices (Khojasteh & Kamali, 2016). A point absorber (PA), however, is considered the most effective technique in terms of power absorption and feasibility; both economically and technically (Guo et al., 2022). It is characterized by a small dimensional floating buoy relative to its surrounding wavelength, and a mooring system to keep the buoy supported at the seabed. The objective of a PA system is to absorb the maximum energy from different wave frequencies which is harnessed by a power take off (PTO) system (Shadman et al., 2018).

Although PA systems can take various configurations, a two-body WEC can also be used to harness the wave energy through the relative motion between the two moving buoys thus creating a better cost-effective solution (Li et al., 2023).

Despite its advantages, a PA is not efficient in harnessing the slow-speed oscillations of the waves which encouraged many studies to design PTO devices that can convert the buoy’s mechanical energy into electrical energy with high efficiency to improve the PA’s performance in rough wave and weather conditions which increased the manufacturing, implementation, and maintenance costs (Piscopo et al., 2017). Also, the use of PA systems in irregular wave conditions is affected by wave frequencies which cannot be considered (Liang et al., 2023).

In 2012, Guedes Soares et al. in Review and classification of wave energy converters, studied various WECs to determine the most effective technologies for offshore implementation in terms of theory of operation and power conversion steps. They found out that converters should be classified according to the power delivered cost which requires geographic and economic factors that are susceptible to change (Guedes Soares et al., 2012).

In 2018, Chen et al. in Performance evaluation of a dual resonance wave-energy convertor in irregular waves, introduced a dual resonance wave-energy convertor. The performance of the converter was studied using the linear wave theory and spectral analysis under different mechanical factors such as internal mass, PTO system damping, and spring stiffness (Chen et al., 2018).

In 2020, Li et al. in Optimum power analysis of a self-reactive wave energy point absorber with mechanically driven power take-offs, studied two types of PTO systems: mechanical motion rectifier (MRR) and non-MMR with dynamic models in conjunction with the WEC system. They created a numerical simulation to analyse the performance of the two systems. The obtained results showed that the MRR system better absorbs power for small wave periods (Li et al., 2020).

This research aims to compare the behaviour of several buoy shapes in waves. The parameter in the proposed analysis is the geometrical shape of the buoy; alterations in which will be made to study the efficiency of the buoy in absorbing wave power which will be assessed based on the buoy’s movement in response to the incident waves. In this paper, various buoys will be designed and built in a 3D numerical simulation with a fixed radius. The models will then be subjected to wave conditions. Finally, the results will be analyzed to determine the buoy shape that achieved the most movement in response to the incident waves.

2. METHODOLOGY

Numerical models of four buoy shapes are built, namely cube, cylinder, cone, and pyramid shapes and used in a computational fluid dynamics software (Ansys) in the hydrodynamic diffraction system (Aqwa) to run simulations with a fixed radius to determine the buoy shape with the most displacement in response to the incident waves.

The theory of Ansys Aqwa in the frequency domain is solving the equations of motion to calculate the response X of a structure in waves for unit wave amplitude as shown in Eq. (1):

$$[-\omega^2 \left(M_s + M_a(\omega)\right) - i\,\omega\, B(\omega) + C]\, X(\omega) = F(\omega) \quad \#(1)$$

where: ω is frequency

M_s is structure’s mass

M_a is added mass (frequency dependent)

B is damping (frequency dependent)

C is hydrostatic stiffness

F is wave force (incident and diffracting forces)

The methodology is composed of the following four stages highlighted in Figure 1:

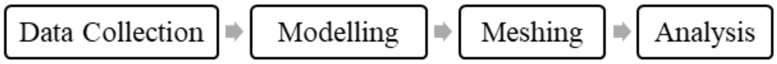

Figure 8: Research Methodology Layout

The simulation is done in a water domain size of 2.5 m × 1.5 m with a depth of 35 m using Ansys Aqwa as shown in Figure 2.

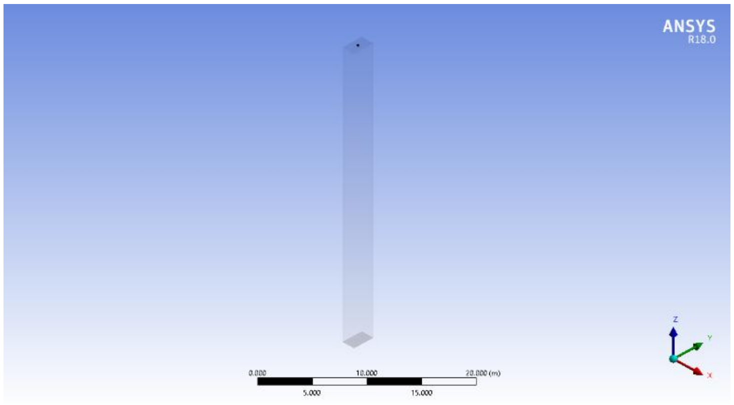

Figure 9: The Water Domain Used in Simulation

In the study, four buoy shapes, cube, cylinder, cone, and pyramid, are 3D modelled and analyzed with a fixed mass of 0.138 kg and a radius of 0.1 m to yield the optimum shape for wave energy harvesting.

The buoys' inertia values are defined through their radius of gyration as shown in Table 1.

Table 23. Radius of gyration of the proposed buoy shapes

Buoy shape	*Radius of gyration*	*Value (m)*
Cube	$k = \frac{l}{\sqrt{6}}$	0.04082
Cylinder	$k = \frac{R}{\sqrt{2}}$	0.07071
Cone	$k = \sqrt{\frac{3\,r^2}{10}}$	0.05477
Pyramid	$k = \frac{l}{\sqrt{10}}$	0.03162

Figure 3 shows the different geometries of the proposed buoys with a radius or characteristic dimension of 0.1 m which signifies the length of the cube, radius the cylinder, cone, and side length of the pyramid where the radius equals the height of the buoy as well.

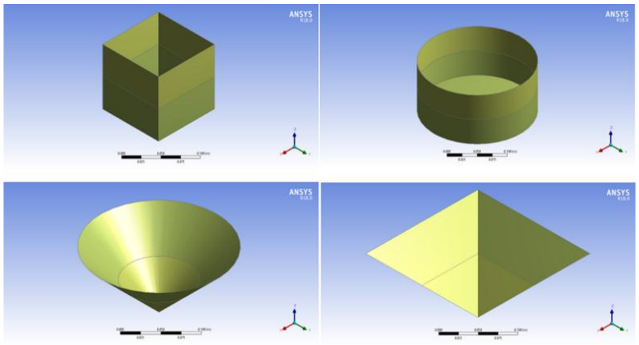

Figure 10: Proposed Buoy Geometries

The buoy shapes were meshed with a maximum element size of 0.003 m as shown in Figure 4. The number of elements is 15680, 30156, 28375, and 17936 for cubic, cylindrical, conic, and pyramidic buoys respectively.

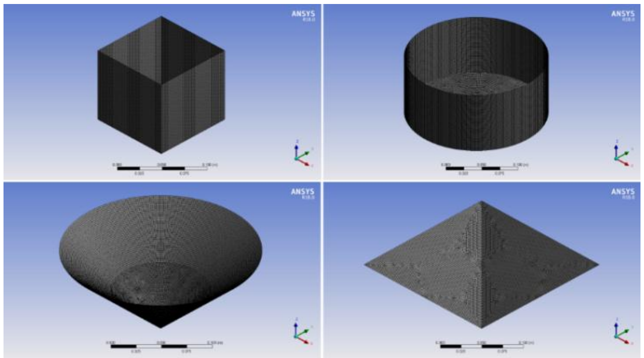

Figure 11: Meshing of the 3D Buoys' Geometries

Four mesh sizes were investigated to verify that the simulation results are independent of the mesh size, with an element size of 0.0033, 0.0031, 0.003, and 0.0029. The total number of mesh elements as well as simulation results are shown in Table 2. The maximum element size of 0.003 was used for the final results.

Table 24. Verification Results of the Simulation Model

Element Size (m)	*Number of Elements*	*Heave Z (N/m)*	*Out of Balance Forces/Weight*
0.0033	13209	98.065681	2.623168
0.0031	14580	98.067108	2.6232119
0.003	15680	98.065903	2.6231372
0.0029	16820	98.065025	2.6231592

The input wave range is -180° to 180° with an interval of 45° resulting in 7 intermediate wave directions as illustrated in Figure 5. The incident wave range has lowest frequency of 0.1 rad/sec and highest frequency of 63.47637 rad/sec and 18 intermediate frequency values.

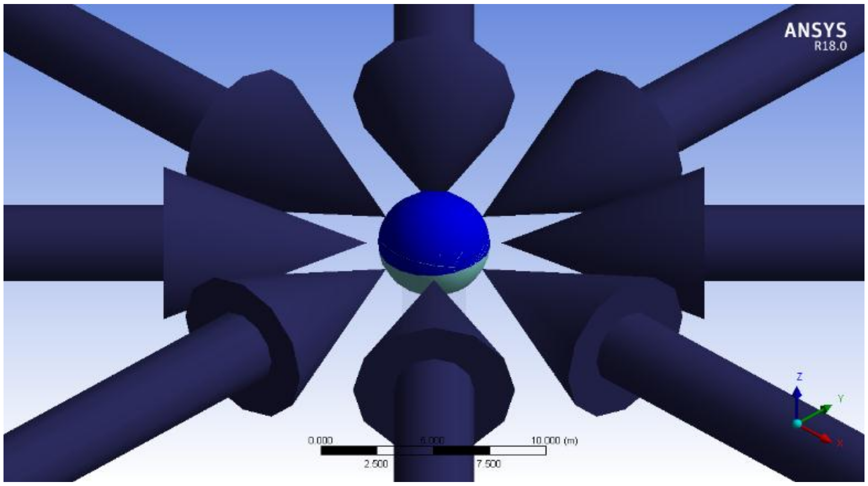

Figure 12: Wave Directions with a 45° Interval

3. RESULTS AND DISCUSSION

The results of the numerical analysis were observed, in incident wave frequency range of 0.1 – 63 rad/sec, with the geometry change of each buoy and the results of the buoy's heave, pitch and roll motions were recorded.

The heave motion of each buoy shape is observed first. Figure 6 shows the values of each buoy's heave motion in the vertical Z-direction. It is observed that the cylindrical buoy yields the highest heave motion with 308.06888 N/m, and the conical buoy yields the lowest heave motion with 77.014214 N/m.

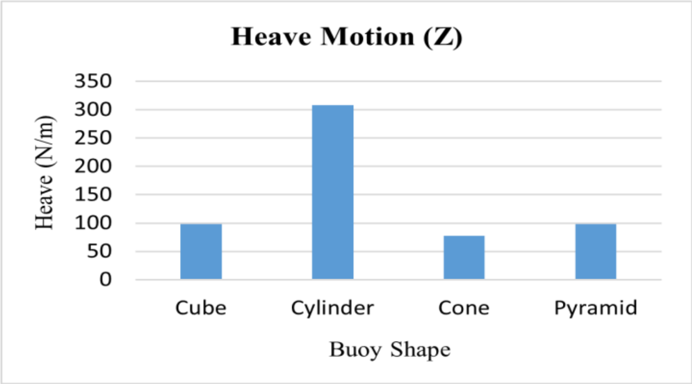

Figure 13: Heave Motion of Proposed Buoy Shapes

The buoys' roll movement in the Z-direction is observed for each shape. Figure 7 shows the values of each buoy's roll motion around the vertical Z-direction. It is observed that the cylindrical buoy yields the highest roll motion with 9.0362×10^{-7} N.m/m, while the conic buoy shape yields the least roll motion with -9.1072×10^{-8} N.m/m.

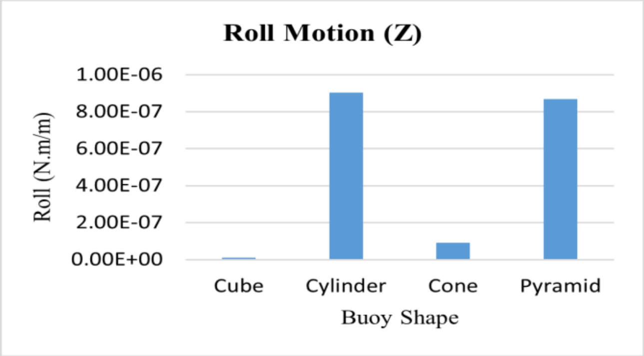

Figure 14: Roll Motion of Proposed Buoy Shapes

The pitch motion of each buoy shape is recorded. Figure 8 shows the values of the pitch motion in the vertical Z-direction for each buoy shape. It is observed that the cylindrical buoy yields the highest pitch motion with 2.2967×10^{-6} N.m/m, while the cubic buoy shape yields the least pitch motion with -9.9922×10^{-8} N.m/m.

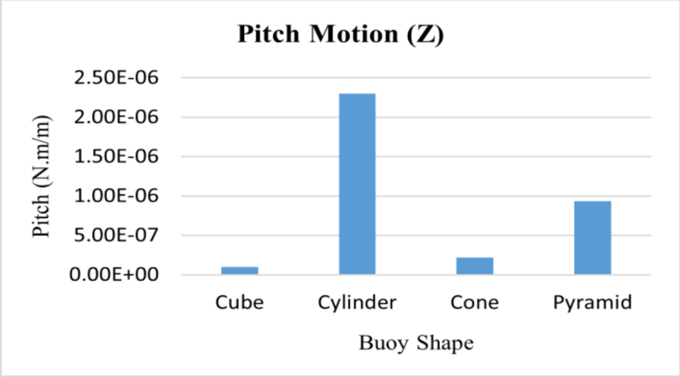

Figure 15: Pitch Motion of Proposed Buoy Shapes

Figure 9 shows the out-of-balance forces affecting the different buoy geometries in the vertical Z-direction. It is observed that a force per unit weight of 10.38197 affects the cylinder, while a minimum force per unit weight of -0.0516 affects the cone.

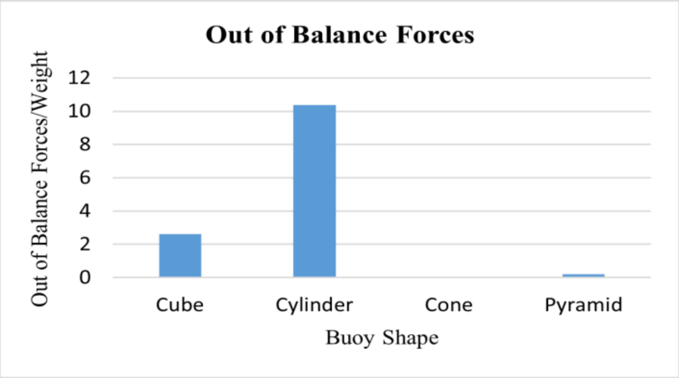

Figure 16: Out of Balance Forces/Weight of the Proposed Buoy Shapes

4. CONCLUSIONS

This study presents a method of evaluating the response of buoy wave energy absorbers based on their motion in the vertical Z direction and the forces that affect the buoys causing their heave motion given the complex interaction between waves and a moving/oscillating buoy which affects its stability as well as energy harnessing efficiency (Yu et al., 2023).

The analysis is carried out by implementing changes in the buoy's geometry and comparing the response of each shape to the out of balance forces generated by the incident waves which is evaluated through the buoys' movement in the heave, roll, and pitch motions.

The four selected geometrical shapes for the buoys are 3D modelled with a characteristic dimension/radius of 0.1 m and a fixed mass of 0.138 kg. The geometries are then meshed with a maximum element size of 0.003.

A range of incident waves from -180° to 180° with an interval of 45° are imposed on each buoy resulting in 7 intermediate wave directions with the lowest frequency of 0.1 rad/sec and highest frequency of 63.47 rad/sec.

The research results show that, for the buoys heave motion, the cylindrical buoy shape yields a heave movement in the Z-direction 52.83% higher than the average achieved motion of 145.3 N/m. The heave motion makes up the largest component of the buoys' motion in the Z-direction.

The out of balance forces are used as an indication of the response of the various buoy designs to the incident waves, which show that the cylindrical buoy is exposed to 68.3% higher value of out of balance forces in the Z-direction than the average value of 3.29 Newton per unit weight.

The results conclude that the cylindrical buoy shape achieves the highest movement values in heave, roll and pitch motions in the vertical Z-direction as well as the highest out of balance forces in the Z-direction making it the most responsive shape to the incident wave conditions analyzed.

In conclusion, the use of cylindrically shaped wave energy absorbing buoys can be efficient and cost effective when compared to other buoy geometries gives the high displacements they reach when exposed to waves. This in turn leads to the increased output of the energy absorbing system while reducing the costs by using the optimum geometry for wave energy harvesting (Zhang et al., 2023).

REFERENCES

- Beirão, P., & Malça, C. (2014). Design and analysis of buoy geometries for a wave energy converter. International Journal of Energy and Environmental Engineering, 5, 1-11. https://doi.org/10.1007/s40095-014-0091-7

- Chen, Z., Zhou, B., Zhang, L., Sun, L., & Zhang, X. (2018). Performance evaluation of a dual resonance wave-energy convertor in irregular waves. Applied Ocean Research, 77, 78-88. https://doi.org/https://doi.org/10.1016/j.apor.2018.04.014

- Guedes Soares, C., Bhattacharjee, J., Tello Ruiz, M., & Pietra, L. (2012). Review and classification of wave energy converters. Maritime Engineering and Technology, 585-594. https://doi.org/10.1201/b12726-82

- Guo, B., Wang, T., Jin, S., Duan, S., Yang, K., & Zhao, Y. (2022). A Review of Point Absorber Wave Energy Converters. Journal of Marine Science and Engineering, 10(10).

- Khojasteh, D., & Kamali, R. (2016). Evaluation of wave energy absorption by heaving point absorbers at various hot spots in Iran seas. Energy, 109, 629-640. https://doi.org/https://doi.org/10.1016/j.energy.2016.05.054

- Li, D., Sharma, S., Borthwick, A. G. L., Huang, H., Dong, X., Li, Y., & Shi, H. (2023). Experimental study of a floating two-body wave energy converter. Renewable Energy, 218, 119351. https://doi.org/https://doi.org/10.1016/j.renene.2023.119351

- Li, X., Liang, C., Chen, C.-A., Xiong, Q., Parker, R. G., & Zuo, L. (2020). Optimum power analysis of a self-reactive wave energy point absorber with mechanically-driven power take-offs. Energy, 195, 116927. https://doi.org/https://doi.org/10.1016/j.energy.2020.116927

- Liang, H., Qiao, D., Wang, X., Zhi, G., Yan, J., Ning, D., & Ou, J. (2023). Energy capture optimization of heave oscillating buoy wave energy converter based on model predictive control. Ocean Engineering, 268, 113402. https://doi.org/https://doi.org/10.1016/j.oceaneng.2022.113402

- Piscopo, V., Benassai, G., Della Morte, R., & Scamardella, A. (2017). Towards a cost-based design of heaving point absorbers. International Journal of Marine Energy, 18, 15-29. https://doi.org/https://doi.org/10.1016/j.ijome.2017.03.005

- Shadman, M., Estefen, S. F., Rodriguez, C. A., & Nogueira, I. C. M. (2018). A geometrical optimization method applied to a heaving point absorber wave energy converter. Renewable Energy, 115, 533-546. https://doi.org/https://doi.org/10.1016/j.renene.2017.08.055

- Viet, N. V., Xie, X. D., Liew, K. M., Banthia, N., & Wang, Q. (2016). Energy harvesting from ocean waves by a floating energy harvester. Energy, 112, 1219-1226. https://doi.org/https://doi.org/10.1016/j.energy.2016.07.019

- Yu, T., Li, T., Shi, H., Zhang, Z., & Chen, X. (2023). Experimental investigation on the wave-oscillating buoy interaction and wave run-up on the buoy. Ocean Engineering, 270, 113631. https://doi.org/https://doi.org/10.1016/j.oceaneng.2023.113631

- Zhang, Y., Wu, W., Zhang, H., & Cui, L. (2023). A controllable-valve buoy for high-efficiency wave energy conversion under a wide range of wave conditions. Ocean Engineering, 279, 114468. https://doi.org/https://doi.org/10.1016/j.oceaneng.2023.114468