INTERNATIONAL JOURNAL OF
COASTAL, OFFSHORE & ENVIRONMENTAL ENGINEERING

IJCOE Vol.7/No. 4/Autumn 2022 (27-36)

Available online at: www. Ijcoe.org

Energy harvesting through an integrated design of a semi-submersible offshore platform with point absorber wave energy converters

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ARTICLE INFO

Article History:
Received: 07 Oct. 2022
Accepted: 14 Feb. 2023

Keywords:
Point absorber
Wave energy converter
Semi-submersible platform
Combined system
Power take-off

ABSTRACT

Increasing the performance of offshore platforms is one of the main aims of the designers. The oil and gas offshore platforms encounter some challenges as the dynamic vibrational response that they always attempt to improve the stability and response of the platforms. On the other hand, many electronic devices on the platform require a supply resource. The transmitted energy of the excited waves into the mechanical vibrations for the platform may be captured by installing some types of WECs. The present study conducts a numerical study on the hydrodynamic analysis of the platform attached with four-point absorber wave energy converters underneath the Amir Kabir semi-submersible platform. The monochromatic regular waves are considered the excitation forces based on the Caspian Sea state. Two different arrangements of WECs and three sizes of sphere buoy are also considered. In addition to calculating the produced power via WECs, the overall performance of the single and integrated platforms is compared from the dynamic response point of view. The results show a considerable difference in the responses of the platform when the WECs are combined. However, the captured power does not depend on the locations of the WECs but is affected by the buoy size of the WECs while the platform response is dependent on the buoy size and also the WECs' arrangement.

1. Introduction

Ocean wave energy is a clean resource. The new technologies related to wave energy converters (WECs) can be used for converting the wave energies to desired energy as electricity[1]. For this reason, many studies have focused on developing different types of WECs [2-4]. Recently due to some economical benefits, these WECs were integrated into fixed [5-8] or offshore structures. Some floating offshore platforms exist whose main role is extracting oil and gas or foundation for offshore wind turbines instead of just being a floating base for installing WECs. These platforms have high-cost technologies; therefore, combining with wave energy converters can overlay reduce the costs and is economical while leading to two merits of additional produced power and reducing the vibrational response of the platforms under environmental excitation forces. Furthermore, sharing the infrastructure, mooring, etc., to minimize the investment is beneficial [9]. Many researchers have recently evaluated the performance of such integrated systems in both aspects of power extraction and total vibrational motion [10, 11]. Generally, a combined offshore structures-wave energy system produces more sustainable energy that is efficient compared to an individual resource.

Ren et al. [2] derived the dynamic response of a monopile combined with a heave wave energy converter under the operational sea states through time-domain analysis and scale model tests. For increasing the power density and reducing the costs of the total project, Muliawan et al. [12] proposed the combined system of a floating wind turbine spar platform with axis-symmetric two-body WECs. They conducted the coupled wave- and wind-induced response-mooring analysis in the time domain to investigate the motion behavior and power production of both wind turbine and WEC under operational conditions. Furthermore, Muliawan [13] investigated the response properties of a combined offshore spar wind turbine platforms with torus point absorber WEC (PAWEC). Wang et al. [14] showed the concave shape of the point absorber WECs results in a better dynamic response and also higher generated power in a combined structure of a 5-MW braceless semisubmersible floating offshore wind turbine (FOWT) attached with WECs. In a similar combined system of an offshore platform attached with PAWECs, Gaspar et al [15], showed that the wave energy converters located at the downwind and upwind sides of the platform create distinct effects on the attenuation of the platform displacements as production of the restoring moments and harvesting the power.

Integrating the flap-type wave energy converters with semi-submersible wind turbine platforms named SFC was also studied through numerical simulation and physical model tests, and it was indicated that the total power of the combined system is increased. Combining a semi-submersible platform with the other types of WEC as a heave-type device has been numerically examined by Aubault [16], in which the optimum PTO system parameters have been derived under typical wave conditions. In the following, Gao et al. indicated that the attached point absorber WECs seem to have a lower cost of energy as compared to the flap WECs attached to an offshore platform [17] regarding the comparison of their total power production, and displacement.

Li et al. [18] suggested a combined design of a heave-type wave energy converter (WEC) with a semisubmersible floating wind turbine to examine the power performance and the dynamic response of the platform through coupled aero-hydro-servo-elastic analysis. Its survivability has been investigated for different possible survival modes [18]. Lee et al. [19] examined the interaction effect of the installed several WEC array on an offshore wind turbine. The WEC arrangement indicates both constructive and destructive effects depending on the wave frequency and direction. The method was based on extracting the hydrodynamic coefficients and exciting forces from WAMIT, and using the 3D diffraction/radiation solver based on the boundary element method.

Combining offshore platforms and oscillating water column WECs has been studied by some researchers [16, 20-22]. Moreover, a new design of the integrated spar platform with OWC WECs arranged in an annular configuration was suggested by Abazari [23]. This proposed design has the advantage of additional generated power besides the wind power and merits of platform dynamic response reduction. Ma et al. [24] combined a semi-submersible wind turbine with tidal turbines. They utilized three-dimensional frequency domain potential flow theory to show the reliability of the power generation system.

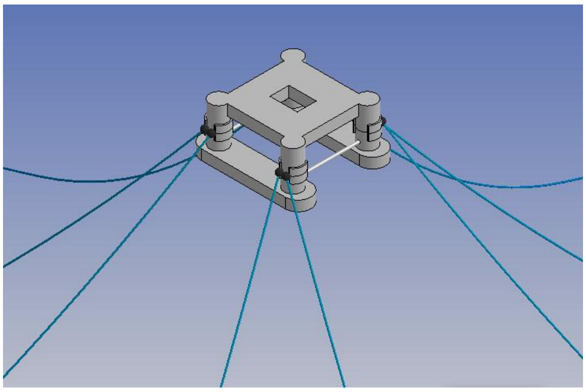
There are other floating devices that are just used for oil extraction as semi-submersible offshore platforms. They have not mostly been considered as a part of combined systems. On the other side, the power supply is required for some of the electronic devices on the platform. For this reason, in the present study, the effects of buoys’ size and arrangement of installed point absorber WECs on the generated power and platform dynamic response are studied. The time domain method based on the potential flow theory is used for analyzing of problem. Therefore, the manuscript is categorized as follows. First, the case study is introduced. Second, the validation of the numerical model in Ansys Aqwa is expressed. Third, the calculation method of the generated power is mathematically introduced. Forth, the results and discussions related to the effects of arrangement and buoys’ size on the power and dynamic response are presented. Finally, a brief conclusion of the present research is determined to evaluate the efficiency and performance of the proposed combined system.

2. Materials and methods

2.1 Case study

The integrated system comprises the Amir-Kabir semi-submersible platform and four PAWEC sphere-type buoys. The platform is utilized in the Caspian Sea in the north of Iran for extracting oil in deep locations. Generally, the wave excitation forces applied on the platform is harsh and may result in a high dynamic response. There are some strategies for motion reduction of the platform that acts as motion dampers, for instance adding heave plates. The heave plates can change the dynamic characteristics of the main floating structure by inducing vortex shedding and added mass[25-27]. However, the new approach of combining WECs into a platform has two benefits: motion reduction and power generation. PAWECs are one of the simple and low-cost devices between WECs [28-30] that are considered for integrating with Amir-Kabir platform.

The proposed idea of attaching some PAWECs may decrease the vibrational displacement of the platform. Additionally, these PAWECs can generate power and supply some electrical devices on the platform. Three schematic views of the platform are illustrated in Figure 1. The main design parameters of the platforms, such as mooring properties and platform dimensions, are presented in Table 1, Table 2, and
Table 3.



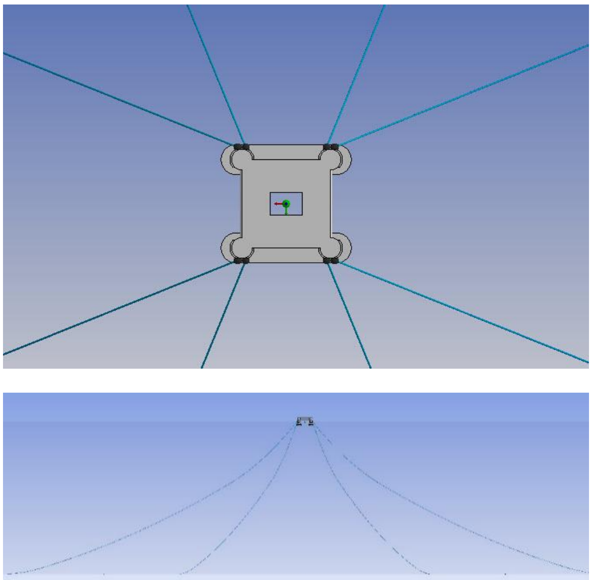


Figure 1. Three different views of the offshore platform demonstrating the mooring configuration

Table 1. Mooring line properties

Water depth	Item	Diameter (mm)	Maximum tension (KN)	Elasticity modulus (Gpa)	Length mooring(m)
1000 m	Upper chain	76	5454	56	900
	Middle cable	86	5101	70	1000
	Bottom chain	76	5454	56	1100

Table 2. Mooring drag coefficient

Item	Drag coefficient
chain	2.6
cable	1.8

Table 3. Geometric dimensions of the Amir-kabir semi-submersible.

Item	value	Item	value
Diameter of columns	12.9m	Height to the upper deck	36.5m
Brace diameter	2m	Breadth outside pontoon	73.4m
Longitudinal distance of columns	54.72m	Length of pontoon	80.56m
Transverse distance of columns	54.72m	Breadth of pontoon	18.68m
Height to the lower deck	28.5m	Height of pontoon	7.5m
Operation draught	19.5m	Total weight of platform	28621 ton
Mass momentum inertias (Kg.m2)	Ixx=2.24E10	Iyy=1.99E10	Izz=3.16E10

Each PAWEC comprises a sphere-type buoy attached to the platform through a PTO system with equivalent stiffness and damping. In fact, the stiffness and damping coefficients are the equivalent mathematical model of a real PTO system that may be a permanent magnet-coil or hydraulic generator [31]. The governing equations of the PTO system coupled with the platform dynamic equation show the same effect as the real PTO system. The interaction between WECs and the platform depends on the induced force in the PTO spring and damper. This force affects their relative displacement which is responsible for the power extraction. The PTO force is defined as below affecting the platform and sphere buoy:

$$F_{WEC-Platform} = B_{PTO}.(\dot{z}_{platform} - \dot{z}_{WEC}) + K_{PTO}.(z_{Platform} - z_{WEC}) \qquad (1)$$

Where $\boldsymbol{B_{PTO}}$ is PTO equivalent damping, $\boldsymbol{K_{PTO}}$ is the PTO equivalent stiffness, $\boldsymbol{\dot{z}_{platform}}$ and $\boldsymbol{z_{Platform}}$ are the absolute velocity and displacement of the platform just above the PTO system, $\boldsymbol{\dot{z}_{WEC}}$ **and** $\boldsymbol{z_{WEC}}$ are the absolute velocity and displacement of the sphere buoy.

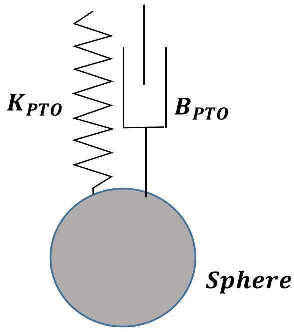


Figure 2. Three main parts of the PAWEC as sphere buoy and spring and damper

The considered stiffness and damping coefficients values are $\boldsymbol{B_{PTO} = 100000\ N.s/m}$ and $\boldsymbol{K_{PTO} = 100000\ N/m}$ is. It is mentioned in the present study the constant values for these coefficients are considered that are not the optimum values. More analysis is required in a wide range of stiffness and damping values to find the optimum values.

The stiffness and damping can be modeled through the fender module in Ansys Aqwa. The fender acts as an integrated equivalent spring and damper such that it has the same mechanical properties as the individual spring and damper. It is noted that the weight and buoyancy force of all sphere buoys are the same. The buoy has natural dynamic stability and is just affected by the induced force of the PTO, which in turn depends on the relative displacement and velocity between the two ends of the fender.

2.2 Calculation method of the extracted power

The PTO system absorbs the vibrational energy of the platform. As mentioned, the PTO system can be a coil-magnet or hydraulic system, so the damping properties of the PTO, modeled mathematically by the damping coefficient, are responsible for converting mechanical energy to the desired one. As the resulting power is a time-dependent harmonic signal, generally, in such conditions, the averaged power in a periodic cycle is computed as equation (2).

$$\bar{P}(\omega)=\frac{1}{T}\int_0^T P(\omega)\,dt =\frac{1}{T}\int_0^T B_{pto}.\left(\dot{z}_{platform}-\dot{z}_{WEC}\right)\left(\dot{z}_{platform}-\dot{z}_{WEC}\right)dt =\frac{1}{T}\int_0^T B_{pto}\omega\,|Z_{P-W}|\cos(\omega t+\varphi)*\omega|Z_{P-W}|\cos(\omega t+\varphi)\,dt =\frac{1}{2}\omega^2 B_{pto}|Z_{P-W}|^2 \tag{2}$$

Where ω is wave frequency, $\dot{z}_{platform}$ is the absolute velocity of the platform just above the PTO system, $-\dot{z}_{WEC}$ is the WEC velocity, $|Z_{P-W}|$ is the steady-state amplitude of the relative displacement between the two ends of the fender.

2.3 Method of fluid dynamic analysis

The dynamic response analysis of the platform under the environmental forces is performed in ANSYS AQWA. The hydrodynamic analysis in Aqwa is according to the ideal potential flow theory, which is a good approximation for the dynamic analysis of objects under the sea wave excitation forces. The value of Froud Krylov, diffraction and hydrodynamic wave forces are calculated based on the diffraction theory in which the total fluid potential function is expressed as the sum of the incident (φ_i), radiation (φ_r) and diffraction (φ_d) potential functions:

$$\varphi=\varphi_i+\varphi_r+\varphi_d \tag{3}$$

The dynamic equations of the platform and sphere buoy have been developed based on newton's second law, and the PTO-induced force has the main contribution to the coupling of their dynamic motions. The solution of the governing equations in Ansys Aqwa is based on the boundary element method. In this method, instead of meshing all parts of the fluid domain, the domain's boundary is just discretized by elements, and then the governing equations can be numerically solved. Therefore, solving the equations is transferred on the domain boundary, reducing the solution time. A schematic view of meshing is presented in Figure 3.

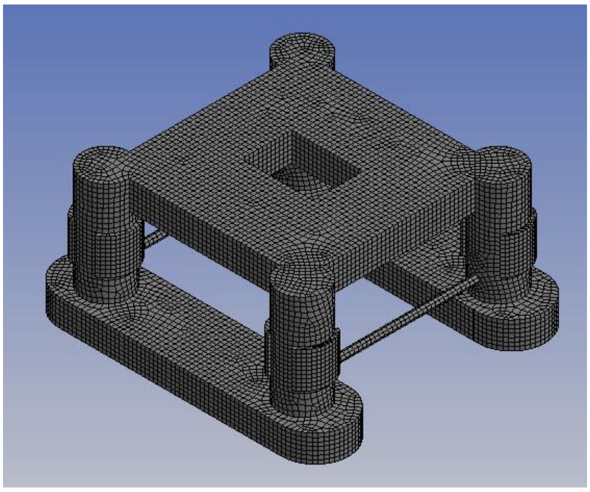
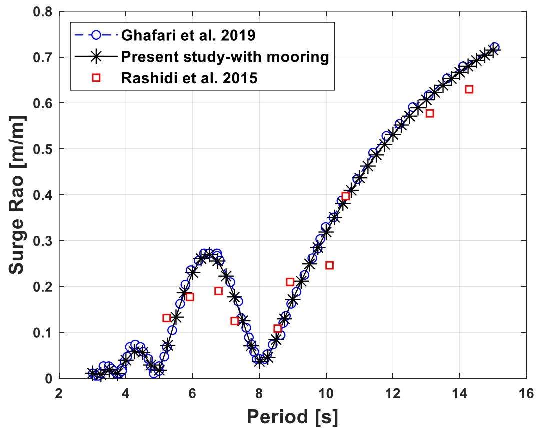


Figure 3. A schematic view of the platform meshing

3. Results and discussion

3.1 Validation

For validation and checking the correctness of the simulation, the RAO response of the platform without WECs is compared with the corresponding results of the same model in the numerical study of Ghafari et al [32] and experimental published works of Ghafarai and Dardel [32] and Rashidi et al [33].



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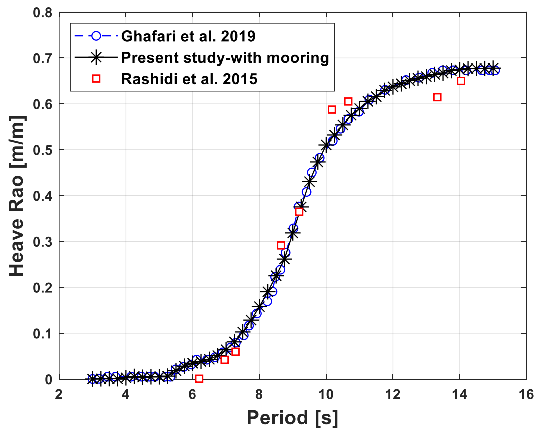

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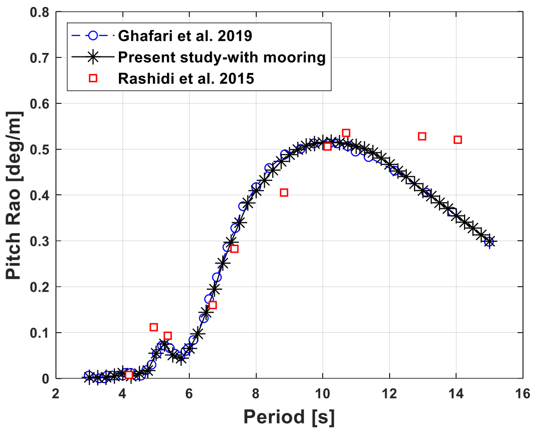


c)

Figure 4. Comparing the RAO response of the offshore platform for three case studies in three directions a) Surge b) heave and c) pitch

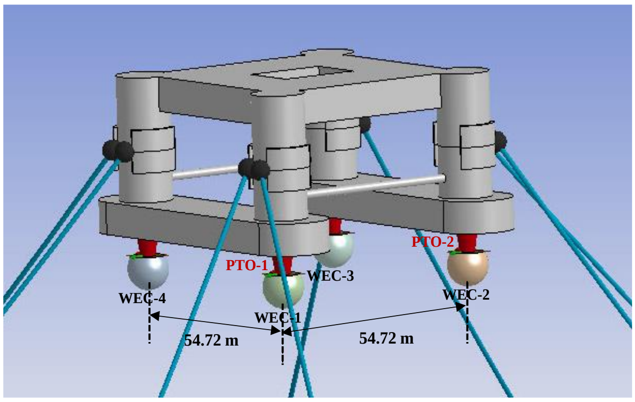
The heave, surge, and pitch RAO responses in Figure 4-a, b, and c show that the results are in good agreement. Furthermore, the effect of catenary mooring on the RAO response is investigated, which indicates a negligible effect. It may be attributed to the fact that catenary stiffness in the heave and surge direction is small compared to the hydrostatic stiffness [33]. This analysis is not existed in Figure 4 to be not messy. Therefore, the applied force from a mooring is not high to affect the platform movement.

3.2. Relative displacement of the fender ends

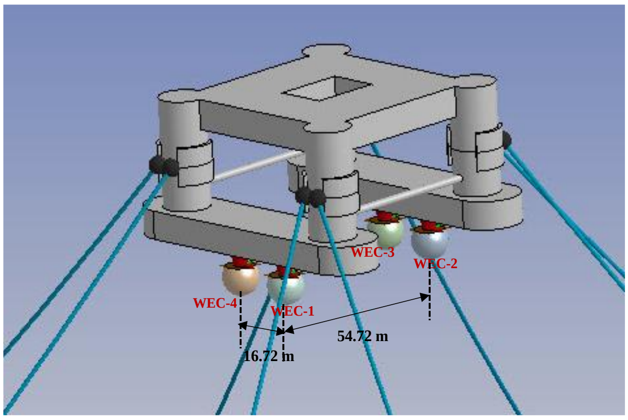
One of the main objectives of this study is to investigate the effects of installing PAWECs on the dynamic response of the semi-submersible platform. For this reason, the PAWECs are considered with different installing locations. Figure 5 shows two configurations of attached PAWECs on the platform such that in case (a), the distance between WECs in the longitudinal direction is higher than the case (b). The dynamic properties of all four installed WECs for the two arrangements are exactly the same.

Locating the WECs at a far distance from the effective waves under the pontoon creates benefits because the sea wave pressure applied on the WEC can induce motion in the buoy of the PAWECs that may increase the total vibration of the platform depending on the wave frequency and system dynamic properties. If the WEC is not affected by the waves, it just oscillates due to its connection with the platform. These oscillations can induce the resisting added mass forces on WECs which in turn can overlay reduce the system's total vibration.

The effect of attached WECs on the platform dynamic response can be accurately seen via time domain analysis, and comparing it with the obtained steady-state amplitude of the single platform is the main criterion for understanding the WEC influences. Moreover, the resulting steady-state amplitude of the relative displacement of WECs and platforms is utilized to derive extracted power. It means that for each WEC PTO, the relative movement between its top and bottom position is crucial. Figure 6 shows a schematic view of a fender simulating the dynamic behavior of a real PTO system. The steady state amplitude of the relative displacement between the top of the fender (point E) and the bottom of the fender (point F) is the main parameter utilized for power calculation.



(a)



b)

Figure 5. Different arrangements of installed WECs with different distances between WECS in longitudinal directions as a) 54.72 m, arrangement A and b) 16.72 m, arrangement B

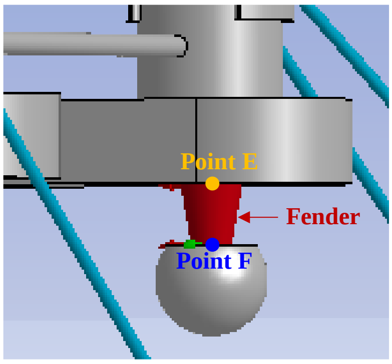


Figure 6. The top and bottom points of the fender

To demonstrate the steady state amplitude of a time signal, for instance, at the excitation period of 15 s and wave amplitude of 3.5 m, the displacement time signals for the mentioned positions for WEC-1 in arrangement A are demonstrated in Figure 7. Cases (a) and (b) are absolute displacements of the platform at point E, the location of the jointing platform with the fender, and case (b) is the absolute displacement at point F, the location of attaching the fender and the sphere buoy. Case (c) is the relative displacement between points E and F.

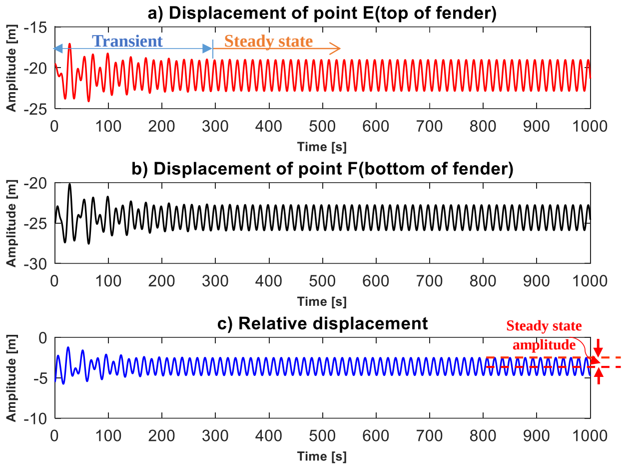


Figure 7. Heave time history for WEC-1 of arrangement A at a) top of the fender, b) the bottom of the fender, and c) their relative displacement at a wave amplitude of 3.5 m

As demonstrated in Figure 7-a, the vibrational amplitude changes in each period at the transient part of each signal until the time it will be a constant value in a steady state condition. A similar repeatable pattern in each period indicates that the state is steady, and this amplitude is the steady state amplitude. The steady-state amplitude of the relative displacement, as shown in case (c), should be replaced in equation (2) instead of $|Z_{P-W}|$ for calculation of the power.

It is noted that the mean position for case (a) is z=-20 m, which indicates that point E attached to the platform oscillates around its equilibrium position 0f z=-20 m. Similarly, the bottom point of the fender or the top of the sphere buoy vibrates around its corresponding equilibrium location at a depth of z=-24 m.

As the semi-submersible is located in the Caspian Sea, the properties of the corresponding sea states for the regular excitation waves are considered. Some values of the most dominant periods, such as 6, 8, 10, 12, and 15 s, are selected based on the Caspian sea state [1]. The wave amplitude of 1.75 m is also assumed for all the regular and incident excitation waves.

The steady-state amplitude of relative displacement between the top and bottom position of each WEC PTO versus period is presented in Figure 8. In arrangement A, where the location of WECs is far from the platform gravity center, the mentioned amplitudes are higher than those for arrangement B.

All the considered regular waves have the direction of 0° relative to the longitudinal symmetric axis at the present work. Therefore, the dynamic motion of spar buoys of all WECs is approximately the same in each of the two arrangements, which is confirmed in Figure 8. The maximum relative amplitude is about T=11 s for arrangement A, while the peak period for arrangement B is higher. The data is determined at the marked points in Figure 8; for the other points between marker points, the other runs are required to clearly show the more accurate trend. However, it is not the scope of the present work, and the overall variation is enough to see the difference between the two arrangements.

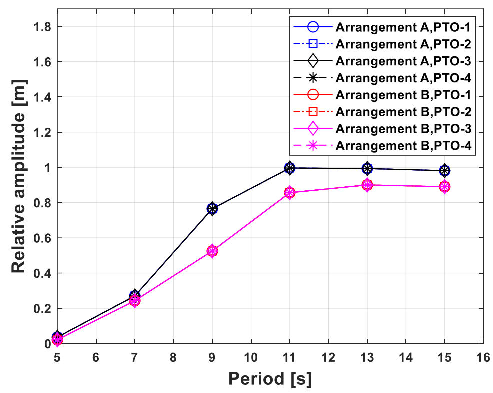
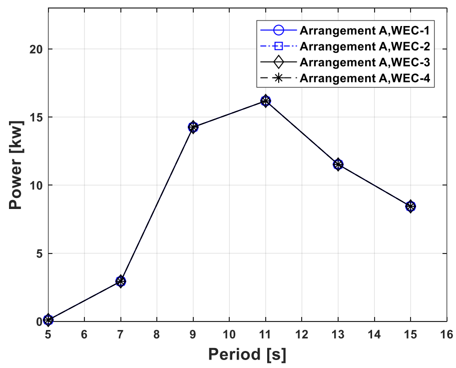


Figure 8. The steady-state heave amplitude of the relative displacement between the top and bottom of WEC PTOs versus the period at a wave amplitude of 1.75 m

3.3. Extracted power of each WEC

The captured power of each WEC versus wave excitation period for arrangements A and B is shown in Figure 9. The maximum power is approximately around the period of T=11 s for arrangements A and B. It is approximately the same as the peak period of relative displacement amplitudes. It is demonstrated that the captured power is the same for all the WECs in each arrangement.



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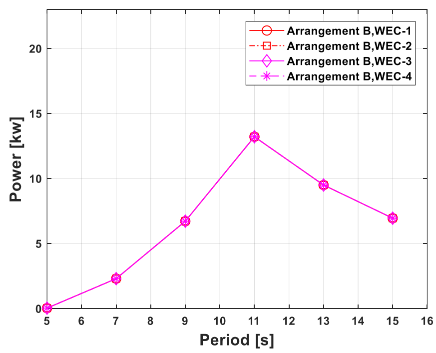


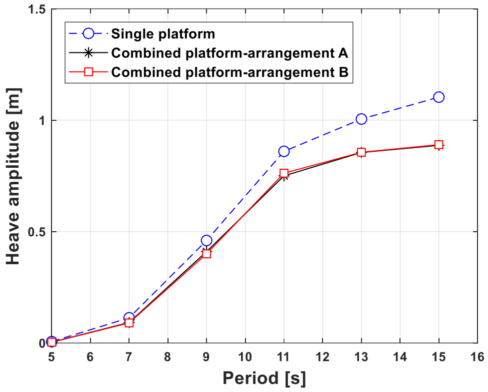
b)

Figure 9. The power of each WEC for a) arrangement A and b) arrangement B at a wave amplitude of 1.75 m

For instance, the total captured power at the period of 11 s for arrangement A with four WECs is about 4*17=68 kw which can supply some electronic devices on the platform.

3.4. Total extracted power and system displacement

Since some part of the mechanical energy of the oscillating offshore platform is captured by the installed WECs, it is predicted that the platform displacement reduces when the WECs are combined with the platform compared to the single situation. Figure 10 shows the steady state absolute heave amplitude versus period. It is indicated that the integrated systems have lower vibrational displacement than the single platform. Moreover, arrangement B considerably results in the same heave and pitch amplitude for the platform as for arrangement A. Therefore, integrating a semi-submersible platform into the PAWEC has two merits: producing power and reducing the dynamic response of the platform, which improves its performance during the operational time.



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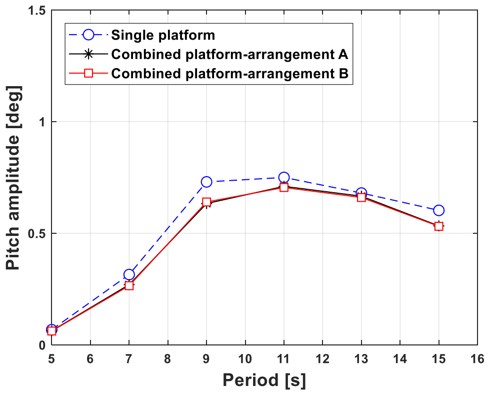

b)

Figure 10. The dynamic response of combined platform for motion direction of a) heave and b) pitch at wave amplitude of 1.75 m

The sphere buoy size is an effective parameter of the WEC dynamic response. Furthermore, the variation of the total generated power versus period at the different sizes of the buoy is investigated. Moreover, that effect on the dynamic response of the platform is also studied. Figure 11 indicates that the increase of the sphere buoy radius increases the total generated power. The peak period of the extracted power is higher for larger sphere buoys. It is shown that the power is small at very small and large values of the period.

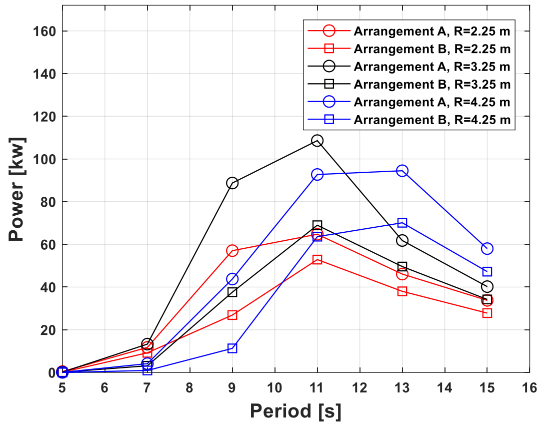

Figure 11. The generated power of arrangements A and B for different sizes of sphere buoy.

Figure 12 shows the effect of the buoy size on the dynamic response of the platform. It is demonstrated that the increase of the sphere buoy reduces the dynamic response in the heave and pitch direction. It may be attributed to this fact that the natural frequency of the oscillating buoy approaches the wave excitation frequency such that the relative displacement of the buoy and platform increases. In this situation the generated power increase and the platform dynamic response reduces. The single platform case is related to a dynamic response of the platform without any attached WECs.

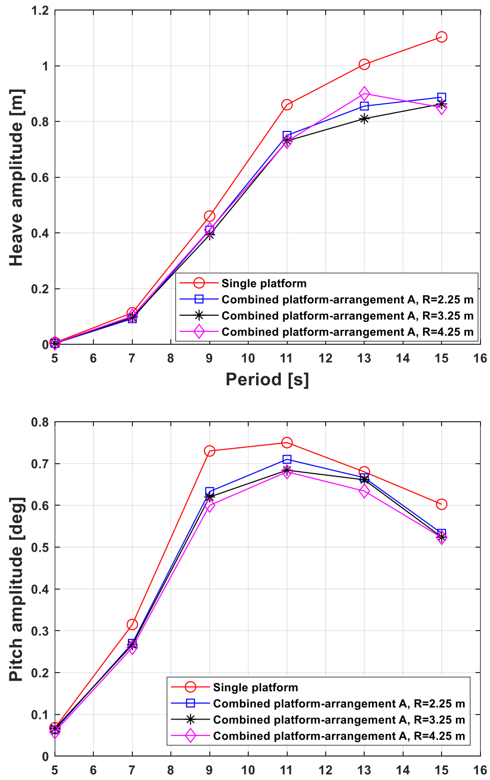

Figure 12. The heave and pitch dynamic response of single platform and combined platform for different sizes of sphere buoy.

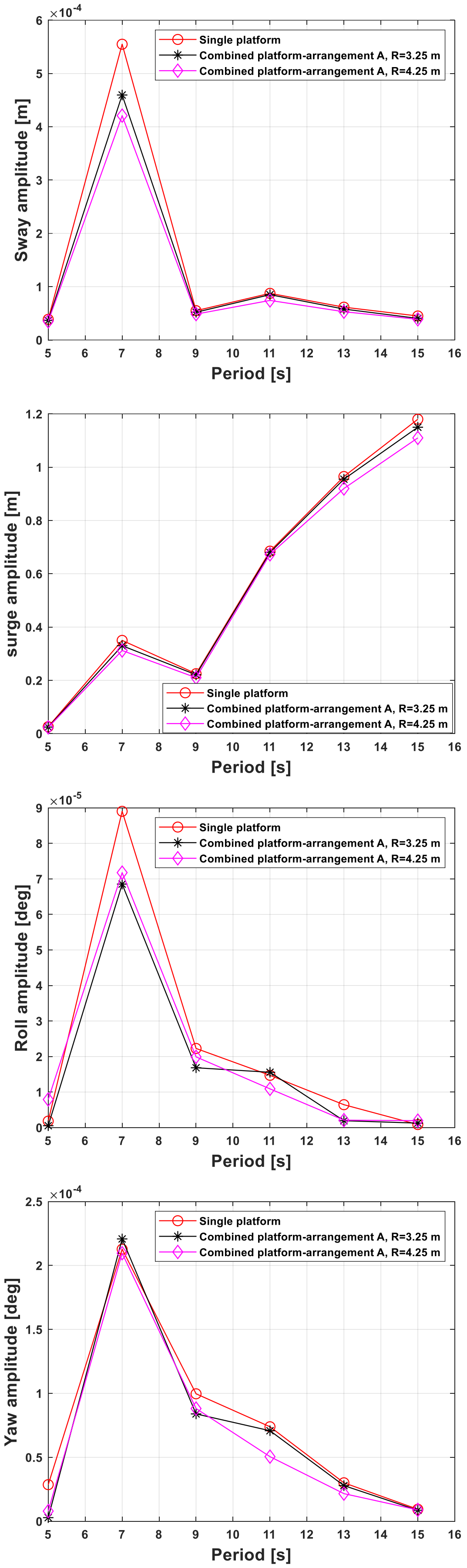

Figure 13. The Sway, Surge, Roll, and Yaw dynamic response of the single platform and combined system at the different sizes of sphere buoy in arrangement A.

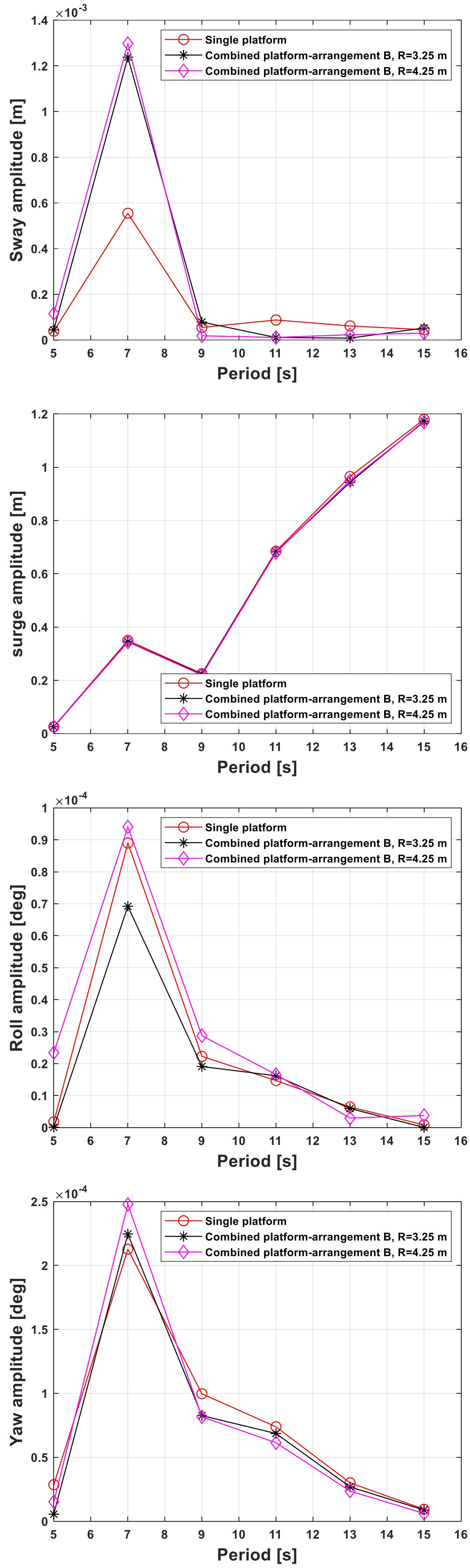

Figure 14. The Sway, Surge, Roll, and Yaw dynamic response of the single platform and combined system at the different sizes of sphere buoy in arrangement B.

Although the heave and pitch response is crucial due to the heave motion of WECs, however, the dynamic response of the combined system of platform and WECs should be examined in the other direction for two sizes of buoys, R=3.25 m, and R=4.25 m.
It is demonstrated from Figure 13 and Figure 14 that arrangement A is more effective than arrangement B. The vibration amplitude of the platform reduces in all directions of sway, surge, roll, and yaw, especially for the larger buoy. However, in arrangement B that WECs are closer to each other in the longitudinal direction, and the roll and yaw vibrations of the combined system are larger than the corresponding vibrations of the single platform. Therefore, arrangement A with a larger distance value between WECs in the longitudinal direction is suggested.

4. Conclusion

Integrating a semi-submersible platform into the wave energy converters as point absorbers can improve its performance. A numerical hydrodynamic analysis based on the potential flow and diffraction theory was conducted via AQWA software in the present research. The boundary element method is utilized for solving the coupled governing dynamic equation of motion related to WECs and platforms. The results showed that the maximum average power of each WEC is between 2-16 Kw at peak periods, depending on the location of the installed WECs. Moreover, the dynamic response of the single and combined platforms indicated that the WECs could effectively reduce the dynamic response of an offshore platform in addition to generating power for supplying electronic devices. An arrangement with installed PAWECs located at a far distance from the platform center is more suggested due to the WEC effects on the motion reduction in all directions and also the power generation.

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