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# Performance evaluation of a hybrid system of dhow ship and wave energy converter for power generation

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## Abstract

One of the main needs for dhow ships is fuel for diesel generators that generate electricity, which in turn is used in refrigerators and electronic devices. Concerning the development of new devices for electricity generation such as point absorber wave energy converters, in the present research for the first time, the feasibility of installing such converters on the hull of the dhow vessel and their performance is being examined. These WECs expanded on the sea-free surface level during anchoring time. Depending on the relative angular displacement between the WEC and the dhow hull, the electricity is produced. In the present study, the simulations are done based on the diffraction theory in Ansys AQWA. The results showed that for considering four installed WECs, the maximum output power of 400 kilowatts is produced, which is an acceptable amount of energy for supplying the common electronic devices on the dhow vessel. In addition to this, it has been shown that the hybrid system of the dhow and WECs in the anchoring mode has fewer dynamic responses compared to a single dhow without WECs. Such conditions can be utilized for the comfort of the passengers or special operations during the anchoring time. It was also observed that the buoy size does not have a considerable effect on the production power and dynamic response of the platform, while the length of 2 m for the lever and angle of 90 degrees of the incident wave is optimum from the production power point of view.

**Keywords:** *dhow ship*, *wave energy converter*, *generated power*, *dynamic response*, *wave period*

## 1. Introduction

One of the traditional barge and fishing boats used on the southern coast of Iran country is a dhow vessel. These vessels are made in traditional and new methods by wood or fiberglass respectively.

**Figure 1. Fishing dhow vessel used in the south of Iran**

Generally, the fishing or cargo dhows are far from the shore and facilities due to their missions. Consequently, they need a power source for supplying electronic devices and refrigerators which is created by diesel generators and a little by solar panels. Climate change and the increase in world demand for energy are the reasons for developing renewable energy technologies. Ocean waves have a higher potential among all clean energy resources [1, 2] such that several different types of resources for energy production from ocean waves have been presented [3-9]. Therefore, in the present study, the feasibility of installing WECs on the hull vessels for electricity production is investigated. The wave energy converters (WECs) are generally installed on fixed or offshore platforms or foundations that do not move. If the dhow ships can utilize the wave energy during sailing the power supply of electronic devices is overcome. However, it is not possible to use the attached WECs during the dynamic motion of the dhow due to the resistance drag and inertia force of WECs. Since such boats travel a long time, there are some times for anchoring in which the boat is still, especially for fishing boats. This time is suitable for expanding the WECs to be able to harvest the kinetic energy of the waves.

There are many studies related to the combination of WECs and offshore structures. The performance assessment of the combined system of oscillating water columns and offshore platforms was studied by many researchers [10-12] and they showed the high efficiency of such designs for power production.

A hybrid wind-wave energy coupling design was suggested through the braceless semi-submersible and Wavestars by Ghafari et al. [13]. By using the time and frequency domain analysis, the output power for different wave heights and wave periods was calculated. Dorostkar et al. [14] and Kamal et al. [15] showed the effectiveness of the hybrid design of point absorber WECs and flap-type WECs in the semisubmersible platforms for power generation and reduction of structure vibrations.

Neisi et al. [16] investigated the performance of the semisubmersible yaw-drive flap combination (SYFC) concept and suggested a hybrid design of flap WEC with a yaw control system to prevent the flap yaw misalignment and enhance the produced power. Moreover, they compared the harvested power of SYFC and semi-submersible flap combination at different wave periods and wave heights. Yazdi et al proposed [17] the new design of a floating braceless semi-submersible platform and an array of Salter's duck (SD) WECs. Its performance with a different number of WECs has been examined under different wave periods and wave heights. The results showed that higher power was absorbed in the wave period of 6–9 s and for zero wave direction maximum absorber power belongs to FOWT-12SD.

There are a few types of research about combining ships and WECs. The effectiveness of an integrated array-point-raft wave energy converter was experimentally investigated under random waves by Yang et al. [18]. Moreover, it was indicated that although the use of more oscillating buoys improves the power quality, but leads to low efficiency at large periods.

A flexible multibody dynamics modeling (FMBD) of point-absorber wave energy converters was developed by Wang et al. [19] which is a combination of multi-body dynamic and finite element methods. They have just focused on structural analysis in which the FMBD model was utilized for computing the stress distributions, modal frequencies, deformations, etc.

As mentioned the performance of the hybrid design of the dhow and point absorber WECs has not been investigated up to now based on the author's knowledge, therefore, in this study, a simulation is conducted based on the diffraction theory and solution of the Laplace equation with the assumption of potential functions. Furthermore, the effect of buoy and lever size and wave direction of the output power and vessel dynamic response is investigated.

## 2. Governing equation

For simulating the dhow boat in the sea conditions a mathematical model of the wave is required. The simple linear Airy wave theory is used for modeling the waves. The potential function of the incident wave is derived based on the solution of the Laplace equation under the continuity condition and boundary condition of the seabed, and the kinematic and dynamic boundary condition of the free surface. Its potential function is as follows:

$$\varphi_I = \frac{H}{2}\frac{g\cosh k(d+z)}{\sigma\cosh(kd)}\sin(kx-\sigma t) \quad (1)$$

The wave force applied on a floating object can be calculated by experimental, analytical, numerical boundary element methods or computational fluid dynamic methods. By considering the ideal flow the second law of Newton for fluids called Navier stokes equations are simplified to Laplace equation as :

$$\nabla^2\varphi = 0 \quad (2)$$

The present research uses numerical BEM for solving the Laplace equations based on the diffraction theory. The potential functions of the waves can be discretized into three different incident, radiation, and diffraction ones. The first one is due to the incident wave responsible for Froud Krylove force, the second is due to the vibration of the object in the calm water that induces the added mass and radiation damping force and the diffraction wave is created when the body size is large enough to diffract the incident wave. By supposing the linear equations the total potential function is the sum of the mentioned wave potential functions.

$$\varphi = \varphi_I + \varphi_D + \varphi_R \quad (3)$$

By using the Bernoulli equation, the fluid pressure is determined at the solution domain, and then by the integral of the pressure on the surface area of the object, the wave force can be calculated.

The frequency domain Analysis is used for determining the added mass, radiation damping, and excitation force. Then by applying the second law of Newton on the floating object the dynamic response is derived based on the time domain analysis in Aqwa.

The power is dependent on the relative rotational displacement amplitude of the WEC and dhow hull, $\theta_{D-w}$, and wave frequency, $\omega$, and PTO damping, $B_{PTO}$, as follows:

$$\overline{P}(\omega) = \frac{1}{2}\omega^2 B_{PTO}|\theta_{D-w}|^2 \tag{4}$$

For calculating of $\theta_{D-w}$, the time history of rotational displacement related to the dhow vessel is subtracted from WEC's rod.

## 3. Case study and modeling

The hybrid system in the present study is a dhow vessel with four-point absorber wave energy converters. The considered dhow ship is the specified Jalbout fishing boat [20, 21] with characteristic dimensions presented in table 1.

**Table 1. Characteristic of the Jalbout fishing dhow vessel.**

| | |
|---|---|
| Length | 27.6m |
| Width | 9m |
| Height | 5m |
| Draft | 3m |

The considered model is simulated in Ansys Aqwa as shown in figure 2.

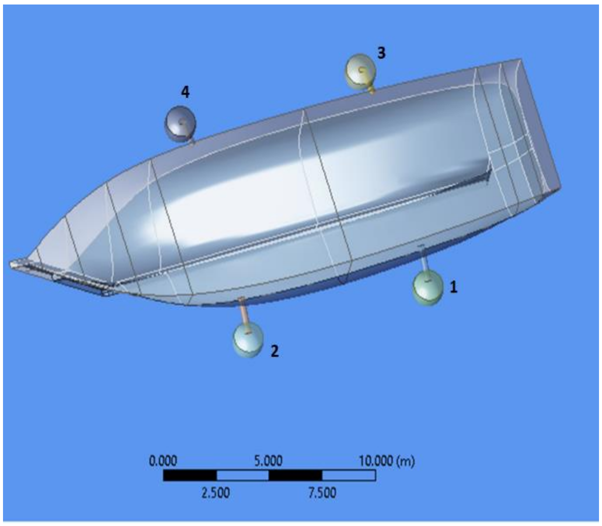


**Figure 2. Hybrid model of dhow vessel and WECs in Ansys Aqwa**

The joint location of the WEC rod attached to the dhow hull is 1.5m higher than the free surface level and consequently o.5 m lower than the dhow deck. The damping of joints is a mathematical model of the power take-off system responsible for power production. Its value is 2864.789 kN.m.s/rad which was selected after several runs in which the maximum power can be captured for the considered case study.

The mass properties of the dhow vessel are presented in Table 1. The considered values of different case studies for effective parameters are represented in Table 2. These values are selected such that they would be suitable for the considered size of the vessel and to be able to examine their effects on output power.

**Table 1- Mass properties of the dhow vessel**

| | |
|---|---|
| Total Mass | 260000kg |
| Center of Gravity X | 7.65 |
| Center of Gravity Y | 0 |
| Center of Gravity Z | -0.98 |
| Moment of Inertia $I_{xx}$ | 982203 kg.m$^2$ |
| Moment of Inertia $I_{yy}$ | 6270000 kg.m$^2$ |
| Moment of Inertia $I_{zz}$ | 9530000 kg.m$^2$ |

**Table 2- The characteristics of different case studies**

| parameter | value |
|---|---|
| Rod length of WEC (L) | 1.5, 2, 2.5, 3 m |
| Buoy radius (R) | 0.75, 1, 1.25 m |
| Wave direction ($\theta$) | 0, 45, 90 degree |
| Wave period (T) | 3, 5, 7, 9, 11, 13 s |

## 4. Results and discussion

In this section, the effect of rod length, buoy radius, wave direction, and wave period on the output power and the dynamic response of the dhow vessel are examined and discussed. For the considered case studies 216 Runs in the time domain were done in Aqwa, however, due to the huge amount of results, just some of them are presented in the present research that properly shows an overall view of the variation trend of the dynamic response and power versus effective parameters of the rod length, buoy radius, and wave angle.

It is noted that the single dhow and hybrid design of dhow-WEC are indicated as acronyms of SD and DW respectively in the legends of the following figures.

### 4.1. Effect of rod length

The rod length of the point absorber wave energy converter is an effective parameter that may affect the dynamic response of the hybrid design of the dhow ship and WEC. For this reason by considering a constant value for bouy radius as 0.75m and wave incident angle of 0 degrees the variation influence of WEC rod length on the dhow motion response and output power are examined. The observed trend for other buoy radius and wave angle are approximately the same. Figure 5 to figure 4 indicate that overall the dhow dynamic motion in all directions reduces as the WECs are utilized compared to a single dhow. It means that some part of the dhow vibrational energy converts to electrical energy. However, the reduction movement at roll and pitch direction for the dhow vessel in hybrid design is more considerable than the other ones. It is attributed to this fact that the WECs act as stabilizers around dhow creating restoring moments. When dhow oscillates rotationally in pitch or roll directions, consequently the attached rods and related buoys tend to move into the water. Then the inertia-added mass forces applied on the spherical surface of the buoys create the resistance force and moments which in turn decreases the vibrations of hybrid dhow and WECs compared to a single dhow without any attached WECs. These opposite forces are related to the moving buoys in still waters. On the other hand, other opposite forces are imposed on buoys and consequently on the dhow vessel due to the wave excitation moments. However, because the positions of WECs at both sides of the dhow are in the same x position along the dhow, therefore, the heave wave forces on the buoys do not affect the excitation moment at roll direction in this point of view. similarly, as the WECs located in the front and aft section of the dhow are approximately the same distance from the center of rotation, therefore, they do not disturb the dhow pitch motions. It seems that the hybrid design of the dhow and WECs has more stability compared to the single dhow due to the resistant added mass force and also due to the dissipation of the rotational vibrational energy of the dhow to electricity by PTO.

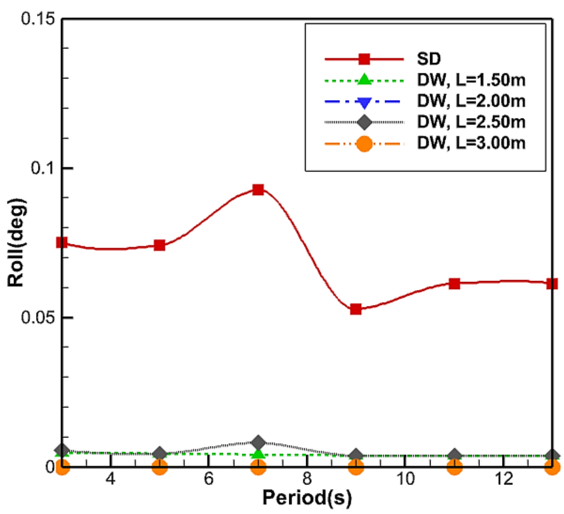


Figure 3. Effect of rod length on dhow roll motion

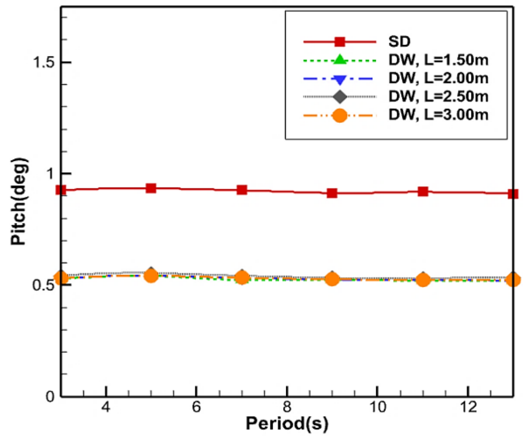


**Figure 4. Effect of rod length on dhow pitch motion**

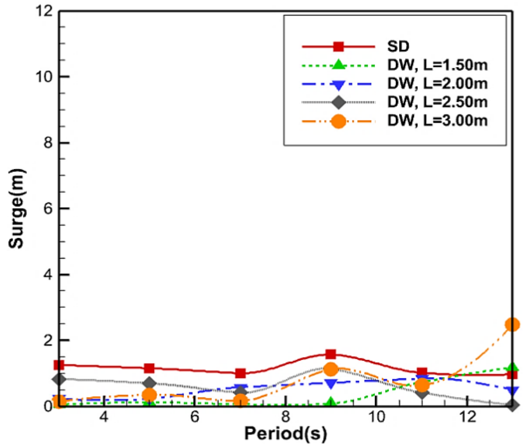


**Figure 5. Effect of rod length on dhow surge motion**

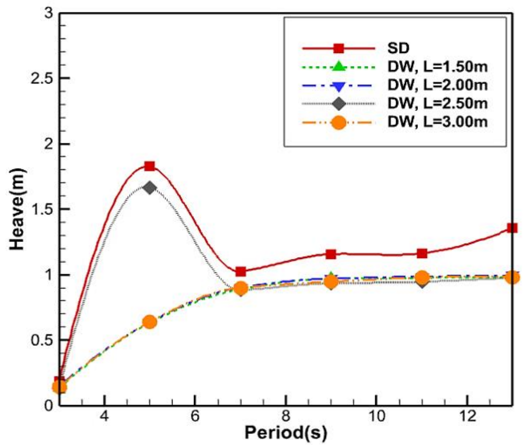


**Figure 6. Effect of rod length on dhow heave motion**

Although the resistance-added mass in heave and surge directions exists which in turn increases the stability of the dow and decreases its movements in all heave and surge directions, however, the heave and surge exciting forces due to incident and diffraction waves induce more vibration in heave and surge. Moreover, the pto damping can dissipate some part of this vibrational energy and convert it to electrical energy such that finally the heave and surge movement is lower for hybrid design in comparison with single dhow.

As the rod length increases the amplitude of roll, surge, and heave of the dhow ship does not alter significantly. However, the rod length of 2.5 m leads to higher oscillations in the mentioned directions. It may be related to the dynamic properties of WECs at a length of 2.5 m that excites the natural frequency of the dhow vessel. Figure 5 and figure 6 show that for the dhow surge amplitude is a little different. By increasing the rod length the surge vibrations increase especially at the common dominant peak period of waves around 8-10 s. The trend of surge amplitude at low and large periods for different values of rod length is unpredicted.

Generally, figure 3-6 indicates that combining WECs does not disturb the dhow stability. It is a crucial point when an appendage adds to a floating abject-like ship, it requires stability during the imposing of exciting incident waves.

The relative angular displacement amplitude between the WEC rod and dhow is responsible for extracted power. The effect of rod length on the mentioned induced rotational amplitude is depicted in figure 7. The results show that WEC number 1 and 3 attached to the related rod oscillates in the same amplitude at the same excitation period. Similarly, the WEC numbers 2 and 4 have the same amplitude. This is due to the symmetric position of the mentioned WCS as shown in figure 2.

As the rod length increases the relative rotational amplitude reduces and when the excitation period increases the oscillation amplitude decreases. On the other hand, the lower oscillation amplitudes of WECs happen at large periods or low frequencies. It means that the extracted power which is dependent on both frequency and amplitude is very small at large periods compared to ones related to lower periods. This concept is observed in figure 8 and figure 9. Moreover, at a specified period the lower rod length concludes to higher power.

There is a structural point related to the WEC rod. The stress analysis of the WEC rod also should be conducted to bear the applied force from a structural point of view. The larger WEC rod creates a higher stress value due to a higher bending moment. Fortunately, the analysis showed the smaller rod length is beneficial in both hydrodynamic responses, therefore this point guarantees that the structural stress can be in the margin region.

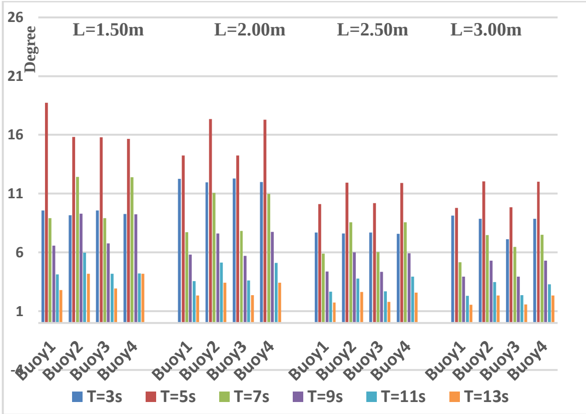


**Figure 7. Relative angular displacement of each WEC to dhow versus period for rod lengths of 1.5, 2, 2.5, and 3m**

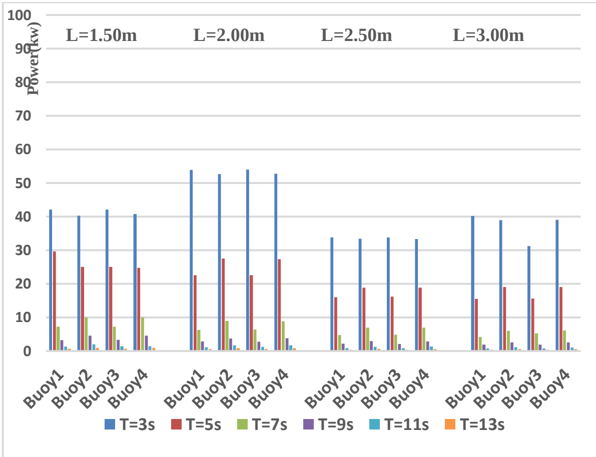


**Figure 8. Generated power of each WEC versus period for rod length of 1.5, 2, 2.5, and 3m**

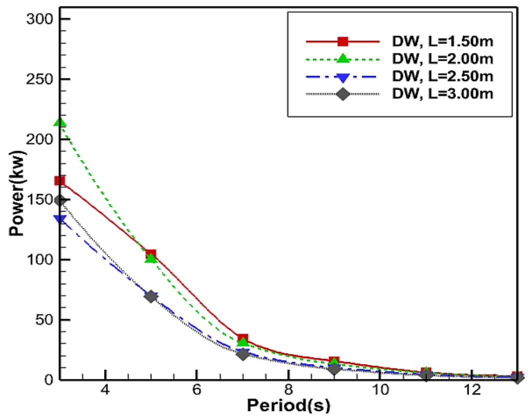


**Figure 9. Effect of rod length on total absorbed power**

### 4.1. Effect of buoy size

The buoy size of the point absorber may be another effective parameter on the dynamic response of the dhow ship and consequently on the output power. For this case, the rod length of 1.5 m and wave angle of 0 degrees is selected.

Figure 10 up to figure 12 show that the combined design of dhow and WECs generally cause a considerable reduction in the vibrational displacement especially in roll, pitch, and heave direction compared to a single dhow. Although, the surge displacement of the combined system is lower than the single one, however, the difference is not as much as one related to the other direction because the surge wave excitation forces are directly transferred to the dhow vessel which increases the dhow surge displacement. However, finally, the effect of surge resistance added mass force overcame surge excitation force such that it led to an observable reduction in surge oscillation for combined design compared to single dhow without any attached WECs.

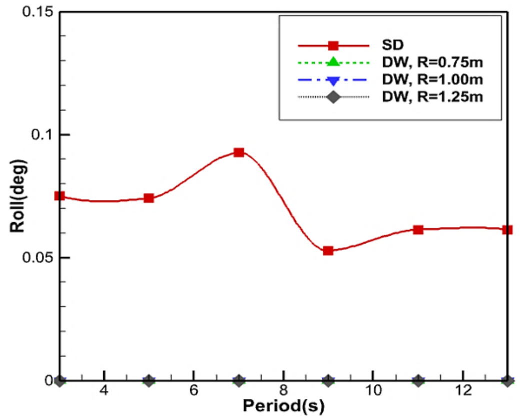


Figure 10. Effect of buoy size on dhow roll motion

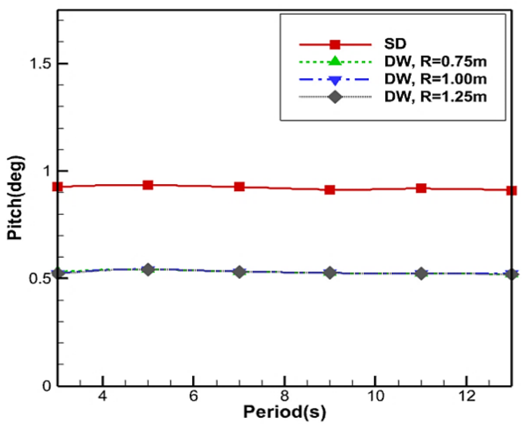


Figure 11. Effect of buoy size on dhow pitch motion

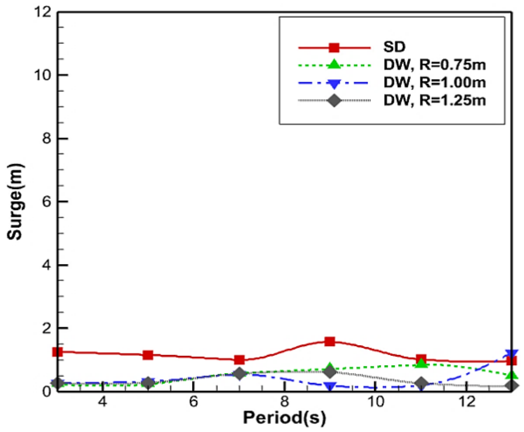


Figure 12. Effect of buoy size on dhow surge motion

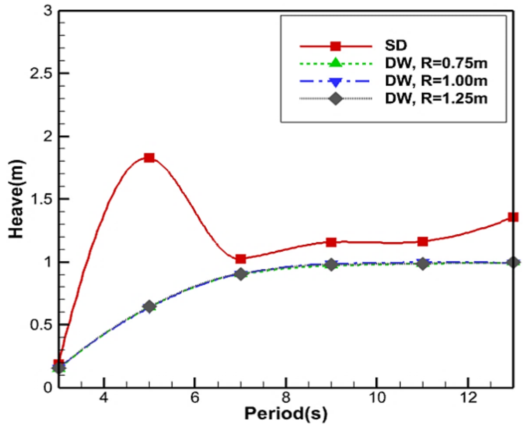


Figure 13. Effect of buoy size on dhow heave motion

Overall, the buoy size for the considered range of radius values doesn't alter the dynamic response in all directions. It means that both effects of resistance and excitation force cannot change the total dynamic response considerably.

As the buoy radius increases the higher relative angular displacement between rod and dhow is derived (Figure 14). However, the relative oscillation amplitude is higher at a lower excitation period or corresponding larger frequencies. Therefore the power which is dependent on both the relative displacement and excitation frequency is high at a lower excitation period and larger buoy size. However, at the large excitation period, the smaller buoy cases capture more power as illustrated in figure 14 and figure 15. It should be noted that as shown in figure 15, the relative displacement and output power are the same for the symmetric location of buoys 1, 3 and buoys 2, 4 due to their symmetric locations relative to the dhow centerline. The total extracted power summing of outpower power of each WEC shows a decreasing trend versus the excitation period as depicted in figure 16.

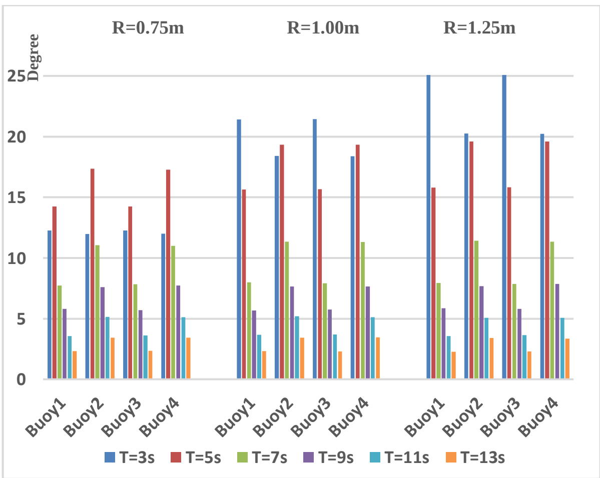


Figure 14. Relative angular displacement of each WEC to dhow versus period for Buoy radius of 0.75,1 and 1.25 m

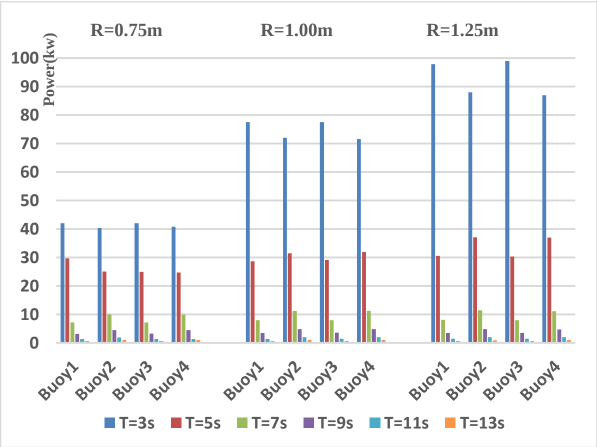


**Figure 15. Generated power of each WEC versus period for Buoy radius of 0.75,1 and 1.25 m**

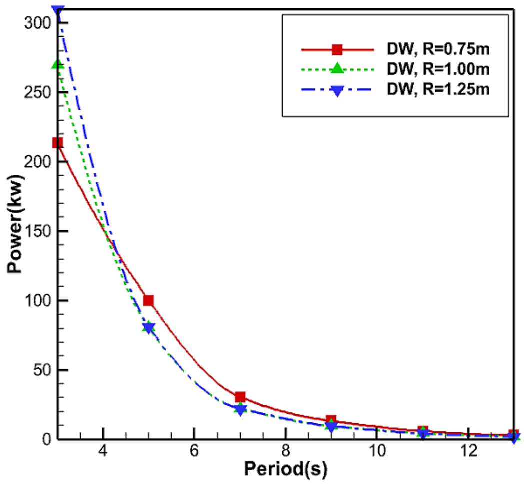


**Figure 16. Effect of buoy size on total captured power**

### 4.1. Effect of incident wave angle

The applied wave direction on the combined system of the dhow and WEC can affect its dynamic response and total generated power.

For this reason, the dynamic analysis of a hybrid system under three different incident wave angles of 0, 45, and 90 degrees is conducted to find and set the best arrangement of the dhow vessel relative to the wave direction. The rod length and buoy radius are considered constant values of 1.5 m and 0.75 m respectively.

Figure 17 and figure 18 show that the single dhow vibrates with a larger pitch amplitude at $0^{\circ}$ because depending on the wavelength, the boat can be inclined between the crest and trough of the wave. The wave angle does not affect the roll and pitch of the dhow in hybrid design, however, at a low excitation wave period the larger wave angle leads to an observable increase in roll oscillation due to more tendency of dhow for inclination at this small wavelength.

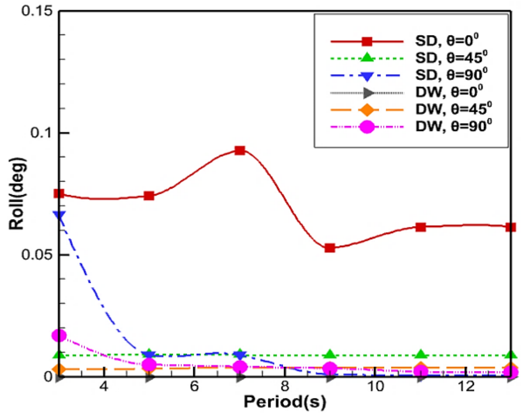


**Figure 17. Effect of wave angle on dhow roll motion**

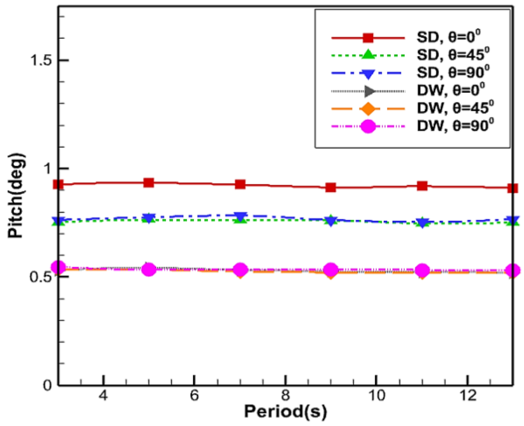


**Figure 18. Effect of wave angle on dhow pitch motion**

Figure 19 and figure 20 show that as the wave angle increases both the single dhow and hybrid design bear higher surge vibration amplitude compared to a smaller wave angle due to asymmetric hydrodynamic load. The heave oscillation for a single dhow is large at the wave angle of $45^{\circ}$ while the heave vibrations of the combined design of dhow and WECs are larger at $90^{\circ}$ just for a short period. The heave amplitude is approximately the same for different wave angles at large wave periods.

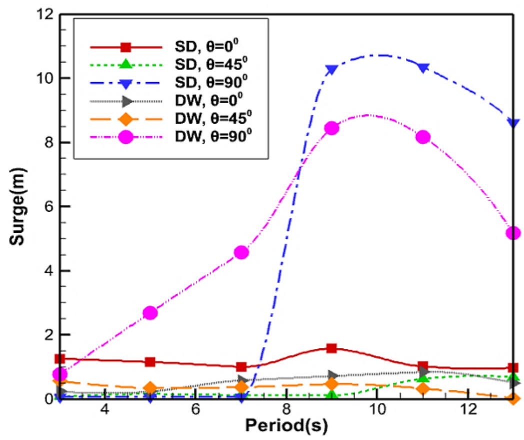


**Figure 19. Effect of wave angle on dhow surge motion**

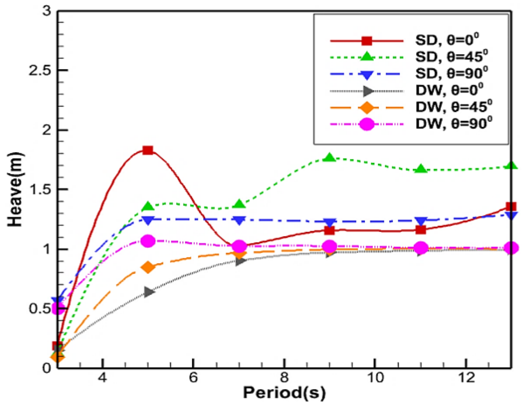


**Figure 20. Effect of wave angle on dhow heave motion**

The total generated power is a key parameter in this study. Figure 21 shows that the wave angle does not affect the output power considerably especially at large wave periods. However, at low wave periods the the wave angle 90° lead to the maximum power. Therefore, in the condition of anchoring time that WECS are utilized for power production if the dhow is turned to be perpendicular to the wave direction, more output power is derived.

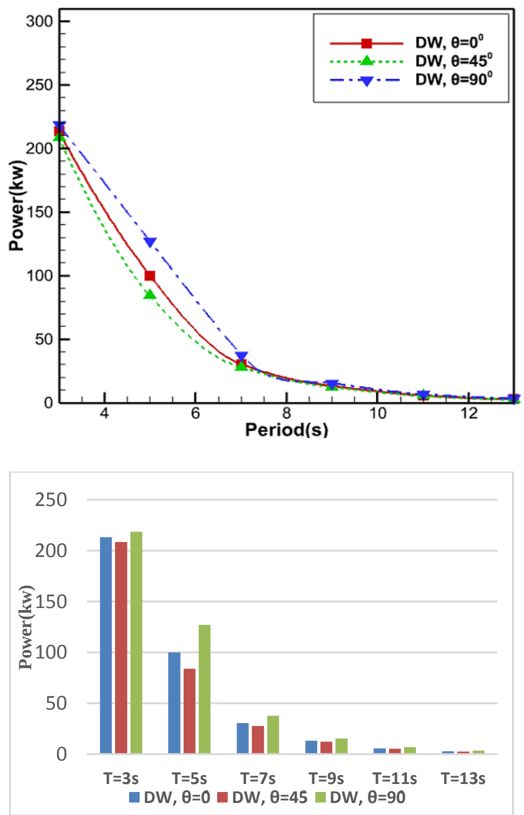


**Figure 21. Effect of the wave angle on total captured power**

It is worth mentioning that the maximum power for all the considered ranges of rod length, buoy radius, and wave angle is about 400 kW as depicted in figure 22.

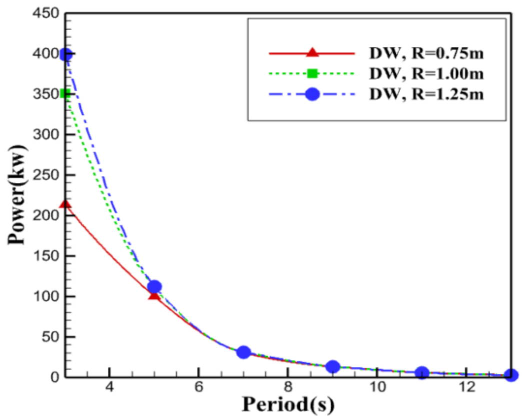


**Figure 22. The maximum power for a rod length of 2 m, buoy radius of 1.25 m, and wave angle of 0°**

## 5. Conclusion

The performance of the hybrid design of the dhow vessel and attached WECs was investigated in the present study through the diffraction theory and numerical approach of the boundary element. The results indicated that generally at common wave dominant period around 6-10 s, smaller buoy size and lower rod length and wave angle of 90° cause the maximum output output power. However, at a small excitation wave period the larger buoy results in higher output power. Moreover, it was illustrated that adding WECs has an additional advantage of vibration attenuation of the dhow ship during anchoring time specifically in pitch and roll direction which is a merit for the comfort of the passenger. The analysis in the present study estimated that the output power of 400kw can be derived for a small excitation period of 3 seconds. It is noted this excitation period occurs in specified sea states which is not very common. However for the common peak period of the Persian Gulf in the ran around 5-6 s the maximum output power of about 70 kW is available.

The requirement power for electronic devices such as refrigerator (fishing Dhow), pumps, and other devices is approximately 7kW. If all devices work 24 hours each day therefore the energy of 168 kWh is needed.

Although the maximum power of 400 kW can be extracted by WECs at specified excitation periods a rough mean value of 70 kW for the WEC extracted power is considered that is assumed to work for just only 8 hours each day in anchoring position for fishing. Therefore the energy of 560 kWh is produced by WECs which is sufficient for supplying all electric devices in Dhow per day that need only 168 kWh.

Moreover, the diesel motor power of the considered dhow vessel is approximately about 180kw. If a dow vessel moves 16 hours each day via its propulsion system then the required energy is around 2880 kWh. The considered arrangement of WECs generates only 560 kWh of which 168 kWh is needed for the electric devices in the Dhow vessel and 392 kWh remains. This residual energy can support 13% of the total required power for the propulsion system if an auxiliary electric motor is installed close to the diesel motor.

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