Power capture performance of a heaving wave energy converter for varying $b_{\text{rad}}/b_{\text{pto}}$ ratio

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Abstract

In this study, power capture performance of a heaving wave energy converter has been optimized by investigating the effect of variation of power take-off damping. The wave energy converter model used in this study utilizes the sliding discrete Fourier transform technique to estimate the local wave frequency. The power take-off parameters are adjusted according to the estimated wave frequency. As a part of the study, two different cases are evaluated. In the first case, the conventional approach based on using power take-off damping equal to radiation damping which is a function of the estimated wave frequency is considered. In the second part of the study, as a proposed approach, the power take-off damping is calculated with a gain factor. This gain factor varies the hydrodynamic analysis-based frequency-dependent radiation damping by multiplying with it. The results show that the captured power results can be increased from 1.64 to 10.38%, while, in average, the power capture increase covering all datasets is 5.95%.

Keywords Wave energy · Radiation damping · Power take-off damping · Energy extraction · Control

1 Introduction

Increasing energy demands, depletion of available energy resources and environmental pollution problems have led researchers towards sustainable, environmentally friendly and alternative renewable energy sources. The most popular renewable energy systems are based on solar and wind energy. Solar- and wind-based renewable energy systems are actively used [1, 2]. The developments in wave energy conversion systems are still in early stages, and they are not as common as solar and wind energy systems.

Considering that the oceans have been reported to have a great wave energy potential [3, 4], there is an obvious high potential for wave energy systems. It has been reported that 20% of the global energy demand can be met by using only the energy captured from waves [5, 6]. This observation made by researchers makes wave energy and wave energy conversion system technologies

a popular research topic. The wave energy, on its own, can be thought of a condensed form of wind energy and can be transferred over the ocean surface for miles with little or no loss [7]. The wave energy converter (WEC) systems are defined as devices that convert the kinetic energy of the wave into mechanical/electrical energy. Generally, a typical WEC system consists of two main subsystems. One of these subsystems is the WEC's body or buoy itself, and the other is the power take-off (PTO) subsystem. There are a number of studies on WEC systems and related PTO types in the literature [8–11].

It is widely known that the oceans have high wave energy potential. However, the main issue is extracting this energy in an efficient manner. There are some methods to improve the power capture efficiency of WEC's. Using nonlinear PTO mechanisms not only improves the captured power but also extends the bandwidth which a WEC can satisfy the quasi-resonance condition [12, 13].

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Hydrodynamic optimization is another approach used to improve the energy capture performance for the intended deployment site and its sea states [14, 15]. An optimization of WEC hydrodynamics may also contribute to its survivability in extreme sea states [16]. Along with these methods, a WEC without any control application is considered as an inefficient energy converter [17]. Hence, a WEC system should be controlled in order to increase the energy extraction efficiency. It is a well-known fact that suitable control algorithm can improve the performance of a WEC system considerably [18]. Typically, a control application of a WEC is actually used to improve the effectiveness of wave energy converter by a considerable amount in percentage [19, 20]. The main question is the selection of the appropriate control technique for the WEC in concern; however, the understanding of the overall issue still remains to be very weak.

The common WEC control strategies are typically based on two main principles. One of them is latching control, and the other is phase control. The latching control strategy is based on using braking forces to lock and release the oscillating body to get a synchronized motion of the WEC body and the PTO system. The latching control can only be applicable if the natural frequency of WEC is greater than the wave excitation frequency [21]. Babarit et al. [22] compared the effectiveness of latching control applications for both regular and irregular sea states.

In phase control, the main objective is to provide resonance conditions by adjusting the WEC's frequency to the incoming wave frequency in order to maximize energy extraction [23]. Mainly the resonance condition is provided by adjusting stiffness of PTO unit (k_{pto}) [24] and/or added mass of the overall system [25]. The PTO parameters must be tuned to the right values at calculated times. This is the key point of a successful implementation of the control application.

Korde et al. [23] reported the details of control parameters and uncertainties in irregular waves. It is worth noting that sub-optimal control applications may lead to decrease the energy conversion efficiency [26]. It was also mentioned [27, 28] that continuously tuning of the device parameters depending upon the incoming waves can maximize the power capture performance of the WEC.

In some PTO applications of WEC systems, a hydraulic system is utilized for power capture [26, 29, 30]. Due to its capacity for generating large force, this type of PTO unit is very much suitable for offshore applications [29, 31]. The optimum conditions for various PTO applications are also mentioned by Kim et al. [32] in order to increase the energy extraction. Also, Falcao [33] utilized a high-pressure hydraulic PTO system for a heaving WEC to optimize hydraulic PTO parameters in time-domain (TD)

model. The hydraulic PTO system mainly has two adjustable parameters. One of them is k_{pto} and the other one is PTO damping (b_{pto}). The theoretical solutions also developed to find the optimal PTO conditions to maximize the extraction performance of wave energy [34, 35]. Zang et al. [36] studied the effects of different parameters including b_{pto} for maximisation of energy efficiency for both regular and irregular waves. The effects of suitably adjusted performance parameters, such as PTO stiffness and the damping, for improvement of the wave energy extraction efficiency are also mentioned in the literature [37–39].

Mainly, the control application on PTO parameters focuses on the stiffness parameter adjustment. However, the damping coefficient is also another performance parameter of hydraulic PTO unit. It is directly related to energy absorbing ability of PTO unit. So, the damping parameter can increase the energy extraction efficiency [40]. Jin et al. [41] showed that applying an appropriate b_{pto} to WEC significantly increases optimum power output. The power absorption efficiency and capacity are directly related to the b_{pto} and also it should be tuned continuously [42].

Falnes [43] reports that the optimum power capture is based on a critical condition. The critical condition is to match the frequencies of the device and the wave. He also mentions that the PTO damping should be set to the same value as the hydrodynamic damping ($b_{pto} = b_{rad}$). As mentioned by Falnes, the b_{pto} is accepted to be equal to frequency-dependent radiation damping (b_{rad}). This forms our first case study. In the second case studied, the b_{pto} is defined as a function of b_{rad} with a gain alpha (α). In definition of the function, the relationship between b_{rad} and b_{pto} is given as ($\alpha = b_{pto}/b_{rad}$). Gain alpha for b_{pto} is chosen as a real number between 0.0 and 3.0. For each sea state, the α is increased from 0 to 3 with the increment of 0.01 to make about 300 simulations. For 8 sea states, these simulations are repeated for the same α range making a total of 2400 simulations.

Using the simulation results, the variation of power performance of a heaving WEC with the different varying ratios of b_{rad} over b_{pto} is investigated. The time-domain model is developed using MATLAB/Simulink™ environment [44]. The control technique of proposed model is established on using online time series analysis of wave elevation data, without predicting the future or knowing the past data. The sliding DFT technique is employed here in order to estimate the wave frequency. The data acquisition of wave frequency has been achieved by processing the wave elevation data. For the simulation study, in total 8 different sea states-related datasets are used varying from calm seas to high seas.

2 Model of the WEC

In the literature, generally mathematical models of floating bodies are developed in frequency domain [32, 43, 45, 46]. Such models are only valid for the regular or sinusoidal form of the input waves. However, the dynamic motion of the free surface of a sea in a real life is almost never in such conditions. Hence, for a more realistic simulation studies it is suggested that the WEC system models should be presented in the TD [27, 47]. A comparison of TD and frequency domain identification process is also presented in [48]. In such modelling approaches, the motion equation of the system should also be presented in TD. For the study presented in this section, the TD model developed by Yavuz et al. [25, 27, 47] is adopted. The main subject of this study is to investigate how the power capture performance of the WEC model changes with the varying b_{pto}/b_{rad} ratio. In order to focus on this issue and prevent repetition, further details, such as hydrodynamic analysis sections of the WEC model and related stages of the modelling details, can be found in references [25, 27, 47].

The Simulink™ model of the system is given in Fig. 1. The input signal to the tuner is based on estimated wave frequency (ω_{est}). So, the optimum k_{pto} and b_{pto} settings can be defined by,

$$k_{pto} = m\omega_{est}^2 - k_{net} \quad (1)$$

and

$$b_{pto} = (b_{rad} + b_{loss}) \quad (2)$$

where b_{pto} is assumed to be simply be equal to b_{rad} assuming that damping loss is zero ($b_{loss}=0$). In the first case of this study, b_{pto} is became and defined as

$$b_{pto} = b_{rad}. \quad (3)$$

In the second case of the study, it is proposed that b_{pto} is defined as a function of hydrodynamic b_{rad} coefficient. Then, Eq. (3) can be written as

$$b_{pto} = \alpha b_{rad}. \quad (4)$$

In our simulation studies, b_{pto} -related calculations will use the definition given in Eq. (3) and Eq. (4) to compare the performance difference. The inputs to the PTO block are x and v provided from the WEC system block. The PTO system-related force is calculated by

$$H = k_{pto}x + b_{pto}v \quad (5)$$

and the instantaneous power (P_{ins}) captured by the WEC is defined by

$$P_{ins} = b_{pto}v^2. \quad (6)$$

A special form of moving averaged PTO power (P_{ma}) is also determined in the relevant block. The P_{ma} is calculated using the relation defined by

$$P_{ma} = \frac{1}{\int_{t_n}^{t_m} dt} \left(\int_{t_n}^{t_m} P_{ins}(t) dt \right) = \frac{1}{T_d} \int_{t_n}^{t_m} P_{ins}(t) dt \quad (7)$$

Fig. 1 Block diagram model of the heaving buoy

where T_d is the time period for the averaging function, t_n is the windows start time and t_m is the end time.

3 Simulation study

The block diagram and further details of the TD WEC model are introduced in the previous section. The main physical dimensions and shape information of the model are presented in Fig. 2.

The main parameters used in the simulation study of the TD model are summarized in Table 1.

The simulations are performed by using the irregular wave elevation data obtained from the real sea state data (DS) used in [28]. Eight different wave elevation data sets derived from real states are used as the input wave elevation data for simulations.

The wave elevation data for each data set can be shown in Fig. 3. The wave height increases with the increasing energy density of the waves. Each wave elevation dataset shown in Fig. 3 is converted into wave force.

Fig. 2 Shape of the modelled WEC

The local dominant wave frequencies of each dataset are also estimated by processing the wave elevation data.

For wave frequency estimation, a sliding DFT algorithm is used [27]. The sliding DFT algorithm is programmed to consider a chunk of data for analysis and it used weighing coefficients that enabled dominance of local data whereas reduced the effectiveness of the old data. In Table 2, the energy density information of each datasets along with some other sea state-related properties is listed. In this table, 1–4 indices means the wave heights are increasing from 1 to 4. The subscription of a and b corresponds to sea site measurements made at two different locations at a reasonable distance. The measurements are taken at almost simultaneously at a nearby location.

Typically, the b_{pto} value is predetermined and kept constant in passive control applications. However, in active control applications, b_{pto} parameter is defined as a function of b_{rad} parameter as given in Eq. (3). In Fig. 4, variation of frequency-dependent b_{rad} with respect to wave frequency is shown clearly. In this study, the b_{pto} parameter is set to be equal to b_{rad} parameter in the first case (Case1). As the second case (Case2), the b_{pto} parameter is varied with the gain α as a function of b_{rad} as defined by Eq. (4).

The radiation damping parameter, presented in Fig. 4, is determined by the estimated wave frequency (in the range of 0.0 to 1.8 rad/s). As illustrated in the figure, a small variation of wave frequency leads to large differences in b_{rad} values.

Hence, estimation of the wave frequency from the wave elevation data becomes very much critical. If the wave frequency estimation is made incorrectly, the system will not be able to select the appropriate b_{rad} and the power capture performance of the system may degrade. In the next part of the study, the results taken from the model is presented and discussed.

Table 1 Properties of WEC model

Parameters	Definition	Value
Inputs	ρ	Density 1 (tonne/m ³)
	dt	Time step 0.2 (s)
	m_{dry}	Dry mass 1369 (tonne)
	D_{wec}	Diameter 12 (m)
	h_{wec}	Height 12 (m)
Computed parameters	m	Total mass 1746 (tonne)
	k_{net}	Stiffness 1134 (kN/m)
	b_{net}	Damping coefficient $b_{inf} + KR(s)$ (kNs/m)
PTO parameters	k_{pto}	PTO stiffness $k_{pto} = f(w)$ (kN/m)
	b_{pto}	PTO damping $b_{pto} = b_{rad}(\omega) * \alpha$ (kNs/m)
	α	Gain alpha 0.0...3.0

Fig. 3 Wave elevation data of four different sea states **Table 2** Results of TD model for irregular sea state dataset

Parameters	Definition	Units	Datasets			
			DS1 _{a,b}	DS2 _{a,b}	DS3 _{a,b}	DS4 _{a,b}
ω_p	Peak frequency	rad/s	0.74	0.70	0.70	0.65
H_{mo}	Significant wave height	m	3.55	4.13	4.65	5.53
$m_o = S(f)\Delta f$	Zeroth-order moment, energy	m ² s	0.79	1.06	1.35	1.91
T_e	Energy period	s	8.29	8.22	8.44	8.95
ω_e	Energy frequency	rad/s	0.76	0.76	0.74	0.70

Fig. 4 b_{rad} as a function of wave frequency

4 Simulation results

This study investigates how the captured power changes with the variation of b_{pto} parameter of the system with the varying ratios of radiation damping. In this part of the study, the results of the simulations are presented. The system is modelled and simulated in MATLAB/Simulink™ software [44]. The wave frequency is estimated by using the sliding DFT technique. The results obtained from the sliding DFT method is used in order to determine both stiffness and frequency-dependent radiation damping. In Case1, b_{pto} used to tune the WEC system is chosen being equal to the radiation damping parameter as shown in Fig. 4. In Case2, b_{pto} is calculated from Eq. 4. Using the range for the gain alpha all b_{pto} values are pre-determined. These results are then used for evaluation of the simulation results thereby optimizing the system performance for eight different sea state datasets.

In Fig. 5a, b, the power capture performance results of the simulation study for different datasets with varying alpha values are presented. The variation of alpha and the captured power levels for different sea states are seen in the figure. It appears that $\alpha > 3$ does not seem to be providing any meaningful results.

In Fig. 5a, the power results for top four datasets are shown. The maximum captured powers at proper gain alpha values are also marked in the plot. It is seen that the best performing alpha gain for DS1_a, DS2_a, DS3_a and DS4_a is observed at 1.86, 1.33, 1.79 and 1.66, respectively.

In Fig. 5b, the power results for second four datasets are shown. The maximum captured powers at high performing alpha gain values are marked in the graph. It is seen that the best settings for DS1_b, DS2_b, DS3_b and DS4_b are gain alpha value of 1.66, 1.58, 1.98 and 1.53, respectively.

The detailed instantaneous and moving average power results for all datasets in time scale are given in Figs. 6 and 7. In both figures, all cases are shown for 1200 s time period. The $\alpha = 1$ terms show the results of first case of the study. The lines coloured as green and blue in the graphs are the power captured of the system where the power take-off damping is adjusted as gain alpha times the radiation damping. This also means the system captures the maximum wave power.

The overall captured power results, covering all datasets, are also presented in Table 3. Table 3 provides overall averages of captured powers for all datasets for both cases along with rated power levels for each set. It is clearly seen that, as the result of the b_{pto} optimization, the captured power is clearly increased. The achieved performance increases in captured power results are observed between 1.64 and 10.38%, while gain factor (α) takes the values between 1.33 and 1.98. The average of alpha value (1.67) and related power capture increase (5.95%) along with dataset specific power captures and alpha values are also provided in the table.

5 Conclusion

In this paper, optimization of the power capture for a heaving WEC by variation of b_{pto} with the ratio of gain alpha is studied. The simulation studies are performed on a TD model. In the first case study, the b_{pto} coefficient is set equal to frequency-dependent radiation damping coefficient (b_{rad}). In the second case study, it is proposed that b_{pto} should be evaluated different from $b_{pto} = b_{rad}$ relation. The PTO damping is remodelled, and the simulations are performed with the varying gain of alpha. The results given in previous part of the study indicated that the power produced is increased, while the b_{pto} is higher than b_{rad} . It was clearly seen that the captured power results are increased between 1.64 and 10.38%. Also, the average of alpha gain value is 1.67 and related power capture increase is 5.95%.

Finally, it can be concluded that there is an obvious need for optimization of b_{pto} in control applications especially while studying for irregular sea state conditions. It can also be stated that the proposed approach based on increasing b_{pto} beyond b_{rad} may be more beneficial than simply assuming that b_{pto} equals to b_{rad} . In such an application the variation of b_{rad} against wave frequency becomes the main tool; therefore, accurate hydrodynamic modelling of radiation damping also becomes a vital issue. Besides, determination of the wave frequency data from wave elevation data also becomes important as it determines the damping coefficient (b_{rad}) used in optimization-related calculations.

Fig. 5 Power outputs (P_{total}) for datasets with variation of α . **a** For datasets [D1_a–D4_a]. **b** For datasets [D1_b–D4_b]

Fig. 6 Instantaneous and moving average power results of [DS1-4]_a

Fig. 7 Instantaneous and moving average power results of [DS1-4]_b

Table 3 Total captured power results for variation of α for DS1_{a,b}–DS4_{a,b}

#	Case1	Case2	α at $P_{\text{total}}^{\text{max}}$	% Power increase $\{ \% \text{ increase} = (P_{\text{total}}^{\text{max}} - P_{\text{total}}) / P_{\text{total}} \}$
	P_{total} (kW)	P_{total} (kW)		
DS1 _a	263.2	285.8	1.86	8.58
DS2 _a	573.2	582.6	1.33	1.64
DS3 _a	651.9	701.0	1.79	7.53
DS4 _a	1280.0	1354.0	1.66	5.78
DS1 _b	297.7	313.7	1.66	5.37
DS2 _b	555.8	582.2	1.58	4.74
DS3 _b	370.7	409.2	1.98	10.38
DS4 _b	1212.0	1256.0	1.53	3.63
		Average	1.67	5.95

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Compliance with ethical standards

Conflict of interest The author(s) declare that they have no conflict of interest.

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