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The Impact of Energy Extraction of Wave Energy Converter Arrays on Wave Climate under Multi-Directional Seas

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Abstract: This paper investigates the energy extraction of three types of wave energy converters (WEC) arranged in arrays and subjected to multi-directional seas of different wave spreading. The changes in the wave climate observed in the neighborhood of the arrays by their energy extraction were also reported. The hydrodynamic software, WAMIT, has been used to generate the performance of the WEC arrays in regular waves, whereas, a post-processing programming code developed in-house has been used to generate the device arrays' performance in multi-directional seas characterized by single-peaked (JONSWAP and Bretschneider) and double-peaked (Ochi-Hubble) wave energy spectra. The results showed interesting findings on the WEC array performance and change in the wave environment around the devices, both strongly depend on the wave energy generation mechanism of the WECs and the wave spreading. The results obtained from the multi-directional seas with double-peaked wave spectrum showed significant differences in the energy production performance by the WEC arrays to those with single-peaked wave spectra. The uni-directional seas resulted in a larger q -factor. The q -factor differed with the peak wave periods, and at small wave periods, the q -factor for the terminator and attenuator WEC arrays are found to be higher than their counterparts for the point absorber WECs. With reference to the

wave height modification in the neighborhood of the WEC arrays, the attenuator generated a greater wave disturbance followed by the terminator and point absorbers.

Keywords: multi-directional sea; wave energy converter array; q -factor; wave climate; double-peaked wave spectrum, energy extraction

1. Introduction

The environmental impact of wave energy converters (WEC) on the wave climate when deployed in an array has been a concern to coastal engineers, marine biologists and environmentalists. The aim of this paper is to address this concern by enhancing the understanding of the WEC's interaction with the wave environment and its impact on the coastal environment as well as the marine ecology.

Three WECs with different means of energy generation mechanism and capture width ratios (CWRs) are considered to assess their influence on the wave climate when arranged in arrays. The three different types of WECs considered are the terminator, the attenuator and the point absorber, and each WEC generates energy via a different means of a mechanism (Falcão, 2010). According to Babarit and Hals (2011), the terminator has the highest capture width ratio of 40% – 60%, followed by the point absorber (14%) and attenuator (7%). In order to present a more realistic case study, the WECs considered here are modelled by taking reference to technologically matured wave energy devices that operate in the shallow water, intermediate water and deep water depth conditions. Thus the properties of the terminator, attenuator and point absorber WECs used in the case study are similar to those of the Oyster 2 oscillating wave surge convertor (OWSC), the Pelamis 1 WEC and the Seabased WEC, respectively.

The performance of the three types of WECs considered in this paper has been studied in the past by various researchers; for example, Renzi *et al.* (2014) on the Oyster 2 OWSC, Retzler (2006) on the Pelamis 1 WEC and Bozzi *et al.* (2013) on the

Seabased WEC. The numerical model developed in this paper shall hence be verified based on the hydrodynamic properties of the WECs presented in the aforementioned papers.

With WEC gaining traction as a potential source of alternative energy to hydrocarbon, various works on WEC arrays have been conducted by wave energy community. Several researchers have investigated a smaller scale array of terminator type WEC. For example, Sarkar *et al.* (2014) and Noad and Porter (2015) investigated the performance of staggered type OWSC arrays operating under regular wave conditions whereas Renzi *et al.* (2014) worked on a single array of in-line Oyster OWSCs. Sinha *et al.* (2015) studied the performance of heaving point absorbers array under regular waves in both linear and circular arrangements with the aim to determine the best possible arrangement of point absorber array for power absorption. Engstrom *et al.* (2013) also analysed the performance of large arrays of point absorber WEC similar to the Seabased WEC and evaluate a method to optimise wave energy farms in terms of power production, economic viability and resource. They claimed that the variance in power production depends crucially on the geometry of the array and the number of interacting devices.

Work on WEC arrays under the uni-directional sea has also been carried out. Among them, Borgarino *et al.* (2012) had looked at the parametric study on WEC arrays and found that grouping the WEC in arrays could potentially lead to constructive effect on the wave interference and thus increased the power output. De Andres *et al.* (2014) also investigated the factors that influence the array layout of wave energy farm made of three to four WECs and found that the interaction factor of the array increased with the number of WECs in the array and the wave directionality played a significant role in achieving constructive interference. Wolgamot *et al.* (2012) and more recently, Bozzi *et al.* (2017) also noticed similar outcomes reported that the wave energy farm has to be oriented in appropriate direction in order to achieve a maximum wave generation.

The literature review showed that most of the studies on the performance of wave energy arrays were conducted considering only regular or irregular waves, and multi-directional seas were least studied. Thus, to the knowledge of the authors, this is the first work that considers the effect of multi-directional seas with both single- and double-peaked wave spectra on the performance of WEC arrays. Three types of wave spectra, i.e. the Bretschneider and JONSWAP both single-peaked wave spectra (Goda, 2010) and the Ochi-Hubble double-peaked wave spectrum (Ochi and Hubble, 1976) are used to generate the multi-directional sea. The occurrence of the double-peaked wave spectrum has been discussed by Soares (1984) and this author reported the importance of incorporating the double-peaked wave spectrum in the prediction of design loads or motions of marine structures, hence including a double-peaked wave spectrum is essential for this study.

The work described in this paper, which is to evaluate the performance of the WEC arrays and the wave elevation surrounding the arrays, are assessed by using the frequency domain approach via the industry standard hydrodynamic software WAMIT (2011). The stochastic post-processing analysis is then performed using MATLAB to obtain the significant wave height from multi-directional sea to assess the wave disturbances surrounding the arrays. The stochastic analysis based on the frequency domain approach is performed instead of the time-domain approach as the computational time by the former approach could be reduced significantly. The differences in the interaction factor and wave disturbance due to the different types of WEC arrays are also compared. The results presented shall enhance the understanding in the design of WEC arrays and shall be useful for wave energy designers and coastal engineers working on optimising the efficiency of the wave farms while reducing their impacts on the environment. It is to be noted that although the terminator, attenuator and point absorber WECs are modelled as close as possible to the actual Oyster 2 OWSC, Pelamis 1 WEC and Seabased WEC, respectively, the results presented should be treated as for generic WECs.

2. Problem Definition

This paper considers arrays of three different types of WECs, i.e. the terminator, the attenuator and the point absorber. The terminator type WEC is shown in Fig. 1(a), which comprises a flap-type floating body hinged at the bottom to a foundation, hence only allowing for the rotational motion about the hinge (pitch, θ_y). Note that the local-coordinate (x, y, z) is located at the hinge. The flap has a width a , immersion depth d , thickness h and the hinge is located at a height c from the sea floor. The attenuator type WEC is shown in Fig. 1(b), which comprises four modules connected by three hinges. The modules are allowed to pitch (θ_y , rotation about y -axis) and yaw (θ_z , rotation about z -axis) at their connected hinge. Note that the local-coordinate (x, y, z) is located at the hinge 2 (see Fig 2b). The attenuator has a total length L , a diameter of $\emptyset$ and an immersed depth $d = \emptyset/2$, where the length of the hinges is assumed to be negligibly small so that each module has an equal length of $L/4$. The point absorber type WEC is shown in Fig. 1(c), which is a floating cylinder with a diameter $\emptyset$ and an immersed depth of d . The floating cylinder is connected to a PTO system located in a foundation hub fixed to the seabed and is assumed to move in the heaving motion (W_z , translation along z -axis). The PTO system is modelled by a force represented by the damping coefficient B_{PTO} to convert the kinetic energy into electricity. The seabed is considered to be flat with a constant water depth of D . The principal dimensions for the terminator, attenuator and point absorbers are presented in Table 1.

Fig. 1. Dimensions for: (a) Terminator WEC (b) Attenuator WEC (c) Point absorber WEC

Table 1. Principal Dimensions and Properties for Terminator, Attenuator and Point Absorber WECs

The array layouts for the WECs are presented in Figs. 2(a) to (c), in which the waves approach the arrays at an angle θ from the Y -axis. Each terminator and

attenuator array has seven WECs and is arranged in a two-row array configuration as shown in Figs 2(a) and 2(b), with four devices at the front row and three devices at the back row. For the terminator array, the devices are spaced at an equal horizontal distance s_p^x of $2a$ and vertical distance s_p^y of a . Note that these are the optimal spacings obtained via an optimisation scheme (Tay and Venugopal, 2016) to produce the maximum q -factor at the operating wave period T . On the other hand, the horizontal spacing s_p^x and vertical spacing s_p^y for the attenuator array are $2L$ and L , respectively, and these spacings are determined to ensure that the devices do not interfere with each other under oblique wave direction. For point absorbers, a four-by-four layout is adopted with 16 WECs in total in the array in Fig. 2(c), where each device is spaced at a constant spacing s_p of $n\emptyset$. It shall be shown in the subsequent section that $n = 5$ for the point absorber array to produce the maximum q -factor at their operating wave period T .

The rigid body motion of the devices together with the total wave elevation surrounding the arrays are generated by using WAMIT. These values are expressed in terms of the response amplitude operator RAO. The stochastic post-processing is then performed in MATLAB to obtain the average q -factor of the array and the significant wave height of the wave climate under multi-directional sea. The details of the post-processing will be discussed in Section 3.

Fig. 2. Array layout for: **(a)** Terminator WEC **(b)** Attenuator WEC **(c)** Point absorber WEC

3. Mathematical Formulation

3.1 WEC under Regular Wave

Consider a generic WEC operating in a constant water depth D as shown in Fig. 3. The WEC is subjected to an incoming wave of wave period T and a wave height $2A$, where A is the wave amplitude, which impacts the structure at a wave angle

θ measured from the Y -axis (see Fig. 2). The motion of the WEC is assumed to be $\mathbf{W} = (W_x, W_y, W_z, \Theta_x, \Theta_y, \Theta_z)$, where W_x, W_y, W_z are the respective translations about the x -, y - and z -axes and Θ_x, Θ_y and Θ_z the respective rotations about the x -, y - and z -axes. The water domain is denoted by Ω whereas the symbols S_F , S_B , S_s and S_∞ denote the boundary for the free surface, the seabed, the wetted surface of the WEC and the artificial boundary at infinity, respectively, as shown in Fig. 3.

Fig. 3. Computational domain for a generic wave energy converter

3.1.1 Governing Equation for Water Motion

The water is assumed to be an ideal fluid with no viscosity, incompressible and the fluid motion is irrotational. Based on these assumptions, the fluid motion may be represented by a velocity potential $\Phi(x, y, z, t)$. We consider the water to oscillate in a steady-state harmonic motion with the circular frequency ω . The velocity potential $\Phi(x, y, z, t)$ could be expressed into the following form

$$\Phi(x, y, z, t) = \text{Re}\{\phi(x, y, z)e^{-i\omega t}\}, \quad (1)$$

The single frequency velocity potential $\phi(x, y, z)$ must satisfy the Laplace equation (Faltinsen, 1993) and the boundary conditions on the surfaces as shown in Fig. 3.

These boundary conditions are given in Faltinsen (1993)

The Laplace equation together with the boundary conditions on the surface S are transformed into a Boundary Integral Element (BIE) by using the Green's 2nd Theorem via a free surface Green's function given in the WAMIT manual (2011) that satisfies the surface boundary condition at the free water surface S_F , the seabed S_B and at the infinity S_∞ . Hence, only the wetted surface of the body S_s needs to be discretised into panels so that the boundary element method could be used to solve

the diffracted and radiated velocity potentials. For details on the Green's function used in solving the BIE, refer to the WAMIT manual (2011).

3.1.2 Governing Equation for WEC Motion

The WEC with a moment of inertia I , Mass m , PTO damping B_{PTO} and hydrostatic stiffness K is assumed to be a rigid body oscillating with a six degrees of freedom rigid body motion $\mathbf{W}(x, y, z, t)$ at a frequency ω and is subjected to wave forces F . $\mathbf{W}(x, y, z, t)$ could then be written as

$$\mathbf{W} = \text{Re}\{W(x, y, z)e^{-i\omega t}\}, \quad (2)$$

where $W = (w_x, w_y, w_z, \vartheta_x, \vartheta_y, \vartheta_z)$ and the corresponding equation of motion is given by

$$\omega^2 MW - i\omega B_{PTO}W + KW = F, \quad (3)$$

where M is the inertia matrix which comprises the mass m and moment of inertia I as given in the WAMIT manual (2011). It is noted that w_x, w_y and w_z are the WEC translation motion along the x , y and z -axes, respectively, whereas ϑ_x , ϑ_y and ϑ_z are the rotational motion about the x -, y - and z -axes, respectively.

B_{PTO} is the optimum PTO damping and is obtained from Eq. (4) for the terminator (Falnes, 2002) whereas B_{PTO} for the attenuator and point absorber WECs are obtained via a trial and error calibration process with hydrodynamic properties found in the literature,

$$B_{PTO} = \sqrt{\frac{[k_{rot} - \omega^2(I + I_a)]^2}{\omega^2}} + B_a^2, \quad (4)$$

where, I_a and B_a are the added inertia and radiated damping, respectively whereas k_{rot} is the rotational stiffness. Note that B_{PTO} varies with respect to the wave frequency ω ; however, the PTO damping is taken as a constant in WAMIT by taking the minimum value of the B_{PTO} generated from (4). This value is found from calibration with known results published in the open literature as shown later in Section 4.

F in Eq. (3) comprises the wave force components which can be derived from the velocity potential $\phi(x, y, z)$ as,

$$F = i\rho\omega \int_S \phi \cdot n_i dS, \quad (5)$$

where ρ is the mass density of the sea water. $(n_1, n_2, n_3) = \mathbf{n}$ and $(n_4, n_5, n_6) = \mathbf{r} \times \mathbf{n}$ (Yasukawa, 1990, Wamit Inc, 2011). The subscript 1, 2 and 3 denote the translation motion about the x, y and z -axes, respective, whereas 4, 5 and 6 denote the rotational motion about the x, y and z -axes, respectively. $\mathbf{n}$ is the unit normal vector which is defined to point out of the fluid domain and $\mathbf{r}$ is the vector of coordinates of the WEC surface. As the velocity potential ϕ in Eq. (5) could be further decomposed into the diffracted ϕ_D and radiated ϕ_R part (Wamit Inc, 2011), this gives us the exciting moment F_e which is derived from the diffracted velocity potential, and the added inertia I_a and radiated damping B_a which are derived from the radiated velocity potential (Wamit Inc, 2011).

Hence, by substituting Eq. (5) into the equation of motion (3), we have

$$\omega^2(M + M_a)W - i\omega(B_{PTO} + B_a)W + KW = F_e \quad (6)$$

Please refer to Wang and Tay (2010) and Tay *et al.* (2009) for the details of the derivation to obtain (6). For N numbers of WECs, the equation of motion of the body n due to the body p is written as

$$\begin{aligned} & \omega^2[M + (M_a)_{nn}]W - i\omega[B_{PTO} + (B_a)_{nn}]W_n + KW \\ & - \sum_{\substack{p=1 \\ p \neq n}}^P [\omega^2(M_a)_{pn} + i\omega(B_a)_{pn}]W_p = (F_e)_n \end{aligned} \quad (7)$$

3.2 WEC Array under Multi-Directional Sea

The three types of wave spectra considered for this work are expressed by Equations (8)-(10). The Bretschneider (denoted as BS) wave spectrum is a fetch-limited spectrum governed by two parameters given as (Goda, 2010)

$$S(\omega) = 5\pi^4 \frac{H_s^2}{T_p^4} \cdot \frac{1}{\omega^5} \exp \left[-\frac{20\pi^4}{T_p^4} \frac{1}{\omega^4} \right], \quad (8)$$

where, H_s is the significant wave height and T_p the peak wave period.

The JONSWAP (JS) wave spectrum is developed for limited fetch North Sea by the offshore industry and is given by (Goda, 2010)

$$S(\omega) = \beta_\gamma \cdot 8.1 \times 10^{-3} \frac{g^2}{\omega^5} \exp \left[-0.032 \left(\frac{g}{H_s \omega^2} \right)^2 \right] \gamma^b, \quad (9)$$

where, the normalising function $\beta_\gamma = 1 - 0.287 \ln \gamma$ (DNV, April 2007), $b = \exp \left[-\frac{(\omega - \omega_p)^2}{2\sigma^2 \omega_p^2} \right]$ and bandwidth parameter $\sigma = \begin{cases} 0.07 & \text{for } \omega < \omega_p \\ 0.09 & \text{for } \omega \geq \omega_p \end{cases}$. ω and ω_p are the wave frequency and peak wave frequency, respectively and g the gravitational acceleration. It is noted here that the shape parameter γ is taken as a mean value of 3.3 following the recommendation by DNV-RP-C205 (April 2007). Also, note that the BS wave spectrum can be obtained by imposing $\gamma = 1$ in Eq. (9).

The Ochi-Hubble (OH) double-peaked wave spectrum (1976) is given by a combination of two uni-directional wave spectra of low and high frequencies denoted, respectively, by subscript $j = 1$ and 2

$$S(\omega) = \sum_{j=1}^2 \frac{\frac{1}{4} \left[\frac{4\lambda_j + 1}{4} \omega_{p,j}^4 \right]^{\lambda_j}}{\Gamma(\lambda_j)} \frac{H_{s,j}^2}{\omega^{4\lambda_j+1}} \exp \left[- \left(\frac{4\lambda_j + 1}{4} \right) \left(\frac{\omega_{p,j}}{\omega} \right)^4 \right], \quad (10)$$

where, $\Gamma(\lambda_j)$ is the gamma function of the spectral shape parameter λ_j . It is noted here that a smaller value of $\lambda_1 = 1$ corresponds to a wider spectrum (swell) whereas a larger value of $\lambda_2 = 2$ to a narrower spectrum (developing sea).

The multi-directional wave spectrum $S(\omega, \theta)$ is then obtained by multiplying the wave spectrum $S(\omega)$ with a spreading function $D(\theta)$ as given in Eq. (11),

$$S_I(\omega, \theta) = \sum_{j=1}^{N_I} S(\omega) \cdot D(\theta), \text{ where } I = \text{BS, JS or OH} \quad (11)$$

where, the spreading function $D(\theta)$ is given by Duarte *et al.* (2014) as in (12).

$$D_j(\theta) = \frac{\sqrt{\pi} \Gamma(s+1)}{2\theta_{\max} \Gamma\left(s + \frac{1}{2}\right)} \cdot \left| \cos \left(\frac{\pi(\theta - \bar{\theta}_j)}{2\theta_{\max}} \right) \right|^{2s},$$

for $-\theta_{\max} < (\theta - \bar{\theta}_j) < \theta_{\max}$, (12)

where, $\bar{\theta}_j$ is the mean wave direction, s the wave spreading parameter and $\theta_{\max} = \pi/2$ in (12). Note that the subscript j in (12) depends on the upper bound of the summation N_I in (11) where $N_I = 1$ for BS or JS and $N_I = 2$ for OH. The gamma function Γ ensures that

$$\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} D(\theta) \cdot d\theta = 1, \quad (13)$$

3.3 Generated Power and Interaction factor

By solving the equation of motion (7), W of the WEC can be obtained. This value can then be used to derive the average power generated by the n^{th} WEC over the range of wave frequency ω considered under multi-directional sea by using the following expression (Cruz *et al.*, 2010)

$$P_I|_n(\omega, \theta) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} (\omega^2 B_{PTO} |W|_n^2) \cdot S_I(\omega, \theta) d\omega \quad (14)$$

Noted also that (14) provides the average power generation $(P_{I=BS,JS \text{ or } OH})_n$ of the n^{th} WEC in the wave energy farm when subjected to the multi-directional sea in the long term statistical sea state.

In order to quantify the interaction between devices, Budal (1977) defines the q -factor which is modified here in Eq. (15) for the multi-directional sea to facilitate the discussion on the performance of the array.

$$q = \frac{\sum_{n=1}^N (P_I)_n}{N \times (P_I)_0} \quad (15)$$

where, $(P_I)_0$ is the average generated power of an isolated WEC and $\sum_{n=1}^N (P_I)_n$ the total average generated power P_I in the array where $I = BS, JS$ or OH depending on the wave spectrum considered. For simplicity, the subscript I will be dropped hereafter and the total average generated power will be referred as P . Equation (15) is used as a performance evaluator for the array where a constructive interaction is denoted by a value greater than 1.0 and a destructive interaction when smaller than 1.0.

In order to quantify the efficiency of the WEC array in generating wave energy, the capture width ratio (CWR) is used and is defined by the following formula (Babarit and Hals, 2011, Tay, 2019, Tay *et al.*, 2018)

$$CWR(\%) = \frac{CW}{L_a} \times 100 \quad (16)$$

where CW is the capture width expressed as the ratio of the average generated power P to the wave power resource $P_{resource}$ (Babarit and Hals, 2011, Tay, 2019, Tay *et al.*, 2018)

$$CW = \frac{P_a}{P_{resource}} \quad (17)$$

where, the wave power resource $P_{resource}$ in (17) is given as (Goda, 2010)

$$P_{resource} = \frac{\rho g^2 T_p H_s^2}{64\pi} \quad (18)$$

3.4 Wave Disturbance under Multi-Directional Sea

The diffracted and radiated wave elevations surrounding the WEC arrays under regular wave could be obtained directly from the WAMIT software. These values, known also as the response amplitude operator (RAO), are expressed as the normalised wave elevation with respect to the incident wave amplitude. In order to obtain the significant wave height of the wave disturbance under multi-directional sea, the squared of the RAO for the total wave elevation is multiplied with the multi-directional wave spectrum as follows

$$S_{res}(\omega, \theta) = \int RAO^2 \cdot S_I(\omega, \theta) d\omega \quad (19)$$

This value is similar to the response spectrum of the array. The significant wave height is obtained as

$$H_s = 4\sqrt{m_0} \quad (20)$$

where, m_0 is the moment of order 0 of spectrum $S_{res}(\omega, \theta)$.

4. Verification of the Numerical Model

The numerical models for the terminator, attenuator and point absorber WECs were verified with the hydrodynamic properties found in the literature review. As most of the properties for the WECs used in this paper are highly confidential with limited data found in the literature, a trial and error process was performed to obtain the WECs' properties by calibrating against those found in Renzi *et al.* (2014) for the Oyster 2 OWSC, Retzler (2006) for the Pelamis 1 WEC and Bozzi *et al.* (2013) for the Seabased WEC. The verification of the numerical model for the terminator WEC was undertaken by Tay and Venugopal (2016, 2017) and will not be shown here. The results obtained from our numerical model were found to be in very good agreement as with those published by Renzi *et al.* (2014). The capture widths of the Pelamis 1 WEC obtained from our numerical model are compared to their counterparts from Retzler (2006) in Fig. 4 where Retzler conducted a model test to investigate the slowly varying drift forces of the Pelamis 1 WEC. It can be seen in Fig. 4 that both the CWs generated by our method and Retzler (2006) have the same peak frequency although the CWs at the lower and higher frequencies differ slightly. The difference could be due to the mooring system not being modelled in the present method and results in the overestimation of the device response at the extreme frequencies. It is to be noted that the attenuator WEC generates energy in two degrees of freedom (DoF), i.e. the pitch and yaw rotation. Thus, the power take-off damping B_{PTO} is taken to be the same for these two DoFs as tabulated in Table 1.

Fig. 4. Capture width for Pelamis 1 WEC. $D = 42\text{m}$, $\theta = 0^\circ$, $L = 120\text{m}$, $\emptyset = 3.5\text{m}$, $d = 1.75\text{m}$

The verification of the hydrodynamic properties of the point absorber WEC obtained from our numerical model with those given by Bozzi *et al.* (2013) is shown in Fig. 5 where the exciting force, added mass and radiated damping are compared. As the results presented by Bozzi *et al.* (2013) were obtained from AQWA, which also adopted the boundary element method approach similar to that in WAMIT, our results match well with their counterparts in Bozzi *et al.* (2013). It is to be noted that the hydrodynamic properties of Oyster 2 OWSC (Renzi *et al.*, 2014) were computed using the semi-analytical method whereas the CWs for the Pelamis 1 WEC (Retzler, 2006) were obtained from model testing. As the methodology used to obtain these results was different from our current model, this could have contributed to the slight discrepancy in the results obtained. Nevertheless, the overall trend of the hydrodynamic properties and CWR agree very well with each other. The principal dimensions and particulars of the WECs calibrated via an iteration of trial and error process are summarised in Table 1.

Fig. 5. Hydrodynamic coefficients for Seabased WEC. $D = 25\text{m}$, $\theta = 0^\circ$, $\emptyset = 5\text{m}$,
 $d = 0.25\text{m}$.

Referring to Section 2 on the WEC array layout for the point absorber, it is suggested that the WEC devices in the array are spaced at a grid configuration at a constant distance of $s_p = 5\emptyset$ in order to maximise the power absorption. The evidence for this is shown in Fig. 6 where the spacing s_p has to be at least $5\emptyset$ for the q -factor under wave direction $\theta = 0^\circ$ to be maximum when operating at the wave frequency $\omega_p < 1.26 \text{ rad/s}$ (i.e. $T_p > 5\text{s}$). A quick comparison of the q -factor in Fig. 7 for the point absorber WEC array spaced at $s_p = 5\emptyset$ in a grid layout (see Fig. 2c) and a staggered layout reveals that the former layout is preferable as it corresponds to a higher q -factor for $\omega_p < 1.26 \text{ rad/s}$.

Fig. 6. Comparison of q -factor of point absorber grid layout under different spacing

$$s, \theta = 0^\circ$$

Fig. 7. Comparison of q -factor between point absorber staggered and grid layout.

$$s_p = 5\phi, \theta = 0^\circ$$

5. Results and Discussion

With the numerical model verified with the existing data found in the literature, the hydrodynamic interaction analysis is then performed on the array layouts presented in Fig. 2 with the particulars given in Table 1. The number of terminator and attenuator WECs formed in the array is the same as those presented in Fig. 2. However, for all the three arrays to generate a total power of 5MW, the number of point absorber WEC in the array has to be increased to 169, arranged in a 13×13 grid layout, where each point absorber has a rated power of 30kW. Note that the terminator and attenuator WEC arrays shown in Fig. 2 also generate an approximately 5MW of power, where each terminator and attenuator WECs has a rated power of 800kW and 750kW, respectively.

The arrays are subjected to multi-directional sea generated using the BS, JS and OH wave spectra. Three different wave spreading parameters s as given in Eq. (12) are considered, i.e. $s = 4, 15$ and 100 . It is noted here that the larger s value, i.e. $s = 100$ corresponds to the uni-directional sea whereas the smaller s value, i.e. $s = 4$ corresponds to a combination of wave components approaching from different directions with the most wave coming from $\bar{\theta}$. The significant wave height H_s assumed for the BS and JS wave spectra is 3m. As for the OH wave spectrum, the H_s for swell sea denoted by subscript $j = 1$ is assumed to be 4m whereas the H_s for the developing sea denoted by subscript $j = 2$ is assumed to be 3m. The spectral shape parameters $\lambda_1 = 1$ and $\lambda_2 = 2$ (see Eq. 10) and the wave peak period $T_{p1} = 15s$

and $T_{p2} = 8\text{s}$ are assumed for the swell and the developing sea, respectively. The spectral shape parameter values are used in order to facilitate the discussion on the effect of the interference between the two different sea states on the performance of the arrays.

5.1 Performance of Arrays

5.1.1 Response of WECs under Multi-directional Sea

The responses of the individual terminator, attenuator and point absorber WECs when subjected to the BS, JS and OH wave spectrum are plotted in Fig. 8 in order to study the motion behavior of the various WECs under multi-directional sea. The types of response for each WEC under wave action are given in Section 2, i.e. pitch for terminator WEC, pitch and yaw for attenuator WEC and heave for point absorber WEC. It is noted that the response θ_s of the attenuator WEC in Figs. 8 and 9 is presented as the total summation of the magnitude response (pitch and yaw) at the three joints of the WEC. Due to the space constraint, only the wave spreading parameter $s = 4$ is considered for discussion. It is to be noted that the responses of the WECs under $s = 15$ and 100 have similar patterns as their counterparts of $s = 4$, but with higher magnitudes when the wave spreading parameter s increases. This is because of the more concentrated wave energy distribution when waves approach from the unidirection.

Figure 8 shows that the responses of the WECs possess similar patterns when the WECs are subjected to the BS and JS wave spectra with the latter having a higher magnitude than the former counterpart due to the higher wave energy content in the JS wave spectrum (please refer to Appendix A for the BS and JS wave spectrum). The response of the terminator WEC is found to increase with the increase of wave period, i.e. wave length and when the wave approaches from the headsea. Hence, this suggests that the response of the terminator WEC is driven by the exciting torque and could be more effective when operating at harsh environment. On the

other hand, the attenuator WEC is effective when the seastate is mild with its optimal performance occurs when the wave period is around 7s to 12s. The motion is also found to be the highest when wave approaches from the headsea with decreasing response when wave approaches from the oblique direction. This is because of the higher pitching motion at the connection joints between the connected modules when subjected to the headsea condition, thus making the turret mooring system more preferable for the attenuator WEC as the device is able to weathervane in accordance to the different wave directions. The response of the point absorber WEC is found to fluctuate with the wave period, and this is more obvious for the JS wave spectrum. However, a closer examination on the range of the response magnitude of the point absorber reveals that the difference between the maximum and minimum response is very small, i.e. less than 0.12m/m, thus suggesting that the wave period does not influence the response of the WEC significantly. In addition, the response of the point absorber WEC does not change with respect to the changes in wave directions due to its axisymmetric geometry.

The responses of the terminator, attenuator and point absorber WECs under the OH wave spectrum are found to be higher than their counterparts of the BS and JS wave spectra. This is due to the higher energy content in the OH wave spectrum as a result of the interference between two groups of wave spectrum (please refer to Appendix B for the OH wave spectrum). However, the patterns of the WECs' response under varying wave directions and wave periods are found to be similar to their counterparts for the BS and JS wave spectra.

The average responses of the three WECs when deployed in arrays and subjected to the BS, JS and OH wave spectra ($s = 4$) are then investigated and presented in Fig. 9. It is noted that the average response is obtained by normalizing the sum of the response of the WECs in the array with the numbers of WEC considered in the array, i.e. $(\sum_{n=1}^N RAO_n)/N$. It is important to note also that the average displacement for each WEC in the array may not be a good measure to quantify the performance of the array as the individual displacement may vary

considerably about the average displacement value. Nevertheless the former is able to provide an overall insight to the performance of the WEC array under multidirectional sea as the average displacement has similar patterns as their individual counterpart presented in Fig. 8. Due to the constructive and destructive interferences as a result of the hydrodynamic interaction between the devices, the effectiveness of the array configurations in generating energy could be quantified by using the q -factor (15), which is a quantity defined as the ratio of the average total power produced in an array to the power produced by an individual WEC. It is noted that the q -factor is related to the WECs' response via Eq. (14) and quantify the efficiency of the array in producing energy (Fig. 9) as compared to its individual counterpart (Fig. 8), where constructive interference is denoted by q -factor value larger than 1.0, and vice versa. This is to say that q -factor greater than 1.0 is desirable as it implies that more energy could be generated by each WEC in the array as compared to a single isolated WEC. The q -factor for the WECs under different wave spectra will be presented in the following sections.

Fig. 8. Performance of a Single Terminator, Attenuator and Point Absorber WECs under BS, JS and OH Wave Spectra. $s = 4$. For BS and JS Wave Spectra: $H_s = 3m$. For OH Wave Spectrum: $H_{s1} = 4m, \bar{\theta}_1 = 45^\circ, T_{p1} = 15s, \lambda_1 = 1; H_{s2} = 3m, \lambda_2 = 2$.

Fig. 9. Performance of an Array of Terminator, Attenuator and Point Absorber WECs under BS, JS and OH Wave Spectra. $s = 4$. For BS and JS Wave Spectra: $H_s = 3m$. For OH Wave Spectrum: $H_{s1} = 4m, \bar{\theta}_1 = 45^\circ, T_{p1} = 15s, \lambda_1 = 1; H_{s2} = 3m, \lambda_2 = 2$

5.1.2 WEC Arrays under Bretschneider (BS) and JONSWAP (JS) Wave Spectra

The performances of the terminator, the attenuator and the point absorber WEC arrays subjected to the *BS* and *JS* (single-peaked wave spectrum) multi-directional

sea are presented in Figs. 10 and 11, respectively. The performance of the WEC arrays is expressed here in terms of the interaction factor, i.e. the q -factor and is plotted against the mean wave direction $\bar{\theta}$ and the peak wave period T_p , where $\bar{\theta}$ ranges from 0° (headsea) to 90° (beam sea) and T_p from 5s to 20s. The maximum $\bar{\theta}$ for the attenuator is however taken only up to 45° as the attenuator is usually weathervane against the wave direction. Figs. 10 and 11 show that the trend of the q -factor for the different types of WEC differs with respect to $\bar{\theta}$ and T_p .

Focusing on the multi-directional sea with $s = 4$, it is observed that the terminator WEC has a higher q -factor with its value greater than 1.0 (denoting constructive interference) when the array is subjected to smaller T_p , i.e. smaller wave length at headsea condition. At headsea direction, the q -factor is found to reduce with the increase of T_p . This is because when the terminator WEC is placed across the incoming wave, they behave like a breakwater, and a greater disturbance is generated as waves are diffracted and radiated, which contributes to the constructive wave interference between the wave energy devices.

On the other hand, the q -factors for the attenuator and point absorber arrays are found to converge to 1.0 with the increase of T_p indicating that the hydrodynamic interactions of these types of WEC arrays when operating at a longer wavelength are similar to their counterparts of a single device. This is because the attenuator and point absorber WECs oscillate at the same phase and amplitude as the incoming wave when the wavelength is large, hence resulting in a smaller relative motion. However, the q -factors for the attenuator WEC array have the opposite trend from those for the point absorber WEC array when T_p is small. It is found that the q -factor for the attenuator WEC array is greater than 1.0 when the T_p is smaller indicating the occurrence of constructive interference. This is attributed to the larger relative movement between the modules in the attenuator WEC and hence generating greater power when the wavelength is small. It is observed from the time series simulation that the radiated waves generated by the attenuator devices could be as small as 1.0m (as a result of energy being extracted from the wave) which contribute

significantly to the constructive interference between the devices. This shows that the diffracted and radiated waves that arise from the presence of the devices aid in increasing the power absorption of the wave farm. For all the WEC arrays, the maximum q -factor occurs when wave approaches from the headsea direction ($\bar{\theta} = 0^\circ$).

Similar observation on the performance of the WEC arrays is also found when s increases to 15. The q -factors for the terminator WEC array are found to be affected significantly by the changes in $\bar{\theta}$ with the increase of s for the whole range of T_p considered whereas the counterpart for the attenuator WEC array is only influenced by the changes in $\bar{\theta}$ when T_p is small. This finding is affected by the absorption bandwidth of the WECs where the terminator is known to have a wider bandwidth (Tay and Venugopal, 2017), hence enabling it to generate energy at a wider range of wave frequency, i.e. wave period.

It can be seen from Fig. 10 that the terminator and attenuator WEC arrays have a higher q -factor when subjected to uni-directional sea, i.e. $s = 100$. This is because the encountered waves have a very small spreading and travel in the headsea direction. This also emphasizes the importance of taking into account the realistic sea by using the multi-directional sea and suggests that the q -factor could sometimes be overestimated if the uni-directional sea is assumed instead of the multi-directional sea. The q -factor for the attenuator WEC array has the same trend for varying s value but in general, it is observed that the q -factor varies significantly with the changes in wave directions at smaller T_p . However, for the attenuator type WECs such as the Pelamis WEC, the device is always weathervane with respect to the incoming waves, thus allowing the WEC to generate maximum wave power at headsea direction. The changes of the q -factor for the point absorber WEC are negligibly small with the changes in wave direction and wave period due to its axisymmetric geometry.

It is also observed from Figs. 10 and 11 that the trend of the q -factor for all three types of WEC under BS and JS wave spectra are similar with respect to the incoming wave direction $\bar{\theta}$ and peak wave period T_p .

5.1.3 WEC Arrays under Ochi-Hubble (OH) Wave Spectrum

The performances of the terminator, attenuator and point absorber WEC arrays when subjected to a double-peaked multi-directional sea are presented in Fig. 12. The OH wave spectrum is used to generate the wind-sea dominated sea state where a swell ($H_{s1} = 4\text{m}$, $T_{p1} = 15\text{s}$ and $\lambda_1 = 1$) interferes with a developing sea ($H_{s2} = 3\text{m}$, $T_{p2} = 8\text{s}$ and $\lambda_2 = 2$). The mean wave direction $\bar{\theta}_1$ and peak wave period T_{p1} for the swell are kept unchanged at 45° and 15s , respectively; whereas $\bar{\theta}_2$ and T_{p2} for the developing sea are, respectively, assumed to vary from 0° to 90° and from 5s to 20s to investigate their effects on the q -factor.

Figure 12 shows that a greater difference in the trend of the q -factor for the terminator WEC array with respect to the changes in T_{p2} and $\bar{\theta}_2$ is observed. This is due to the greater absorption bandwidth of the terminator WEC in which the device is able to generate energy from the interference of the two sea states with different T_p and $\bar{\theta}$ value. On the other hand, as the attenuator WEC is more effective in generating wave energy when subjected to the headsea condition, minimal changes are observed in the trend of the q -factor when subjected to the double-peaked sea state where the developing sea comes in the 45° direction. However, some changes in the q -factor are observed when the T_{p2} is small due to the interference with the developing sea albeit in a small amplitude. The variations occur at the T_p value that coincides with the natural period of the attenuator WEC, i.e. $T_N = 7\text{s}$ ($\omega_N = 0.14\text{ Hz}$), thus suggesting that the intensity of hydrodynamic interaction between the devices is magnified when resonance occurs.

In Fig. 13, the interference of the developing sea with the swell approaching from the same direction, i.e. $\bar{\theta}_1 = 0^\circ$ is investigated. It can be seen that due to the greater

wave energy when two waves coincide in the same direction, the maximum q -factors for all three types of WEC arrays are slightly higher. Owing to the axisymmetric geometry of the point absorber WEC, it can be seen that the trend and magnitude of the q -factor do not differ significantly with respect to different wave spectra.

Fig. 10. Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under BS Wave Spectrum for Different s . $H_s = 3\text{m}$.

Fig. 11. Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under JS Wave Spectrum for Different s . $H_s = 3\text{m}$.

Fig. 12. Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under OH Wave Spectrum. $\bar{\theta}_1 = 45^\circ$.

Fig. 13. Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under OH Wave Spectrum. $\bar{\theta}_1 = 0^\circ$

5.2 Wave Climate Surrounding Arrays

The wave disturbance is represented by the significant wave height $(H_s)_{wf}$, which is obtained via post-processing of the regular wave elevations approaching from different directions as given in Eqs. (19) and (20). Three different spreading parameters $s = 4, 15$ and 100 are considered. The array layout as presented in Figs. 2(a) and (b) are used for the terminator and attenuator WEC arrays, respectively, where the terminator WEC array has a computational domain of $600\text{m} \times 1,200\text{m}$ whereas the attenuator WEC array has a computation domain of $1,400\text{m} \times 3,000\text{m}$. Similar to the performance analysis of the point absorber array as presented in the

previous section, 169 number of devices arranged in a 13×13 grid layout is used where the computational domain is taken as $400\text{m} \times 1,800\text{m}$. The computational domain of the arrays for these three types of WEC is different as it depends on the attenuated wave downstream the array which will be presented in the subsequent sections.

5.2.1 Single-peaked Wave Spectrum Multi-Directional Sea

Effect of Headsea Direction

The significant wave heights of the wave field $(H_s)_{wf}$ surrounding the terminator, attenuator and point absorber WEC arrays subjected to the multi-directional sea modelled using the BS wave spectrum are presented in Fig. 12. The mean wave propagation direction considered is $\bar{\theta} = 0^\circ$ and the significant wave height for the BS wave spectrum is $H_s = 3\text{m}$. The wave disturbances upstream and downstream of the array depend significantly on the mechanism of wave generation by the WECs. In general, it can be seen from Fig. 14 that the maximum wave height of the wave disturbance due to the presence of the WEC arrays is the highest for the attenuator WEC array, followed by the terminator and point absorber WEC arrays. It can also be seen that the maximum $(H_s)_{wf}$ occurs at the wave field near the WECs due to the greater interaction of the diffracted and radiated waves; and these wave elevations are found to be attenuated when they are propagating away from the arrays. The presence of the highest $(H_s)_{wf}$ in the wave field surrounding the attenuator array is attributed to the greater intensity of waves being radiated by the attenuator WECs. The intensity of the interaction between the diffracted and radiated waves will affect the wave attenuation at the downstream of the array. For the case when $s = 4$, the wave interaction is the greatest for the attenuator WEC array, hence explains the occurrence of the slowly attenuated waves downstream of the array as compared to their counterparts of the terminator and point absorber WEC arrays. Note that this phenomena can be checked by observing the $(H_s)_{wf}$ of

the wave disturbance, where the wave is fully attenuated when it approaches $H_s = 3\text{m}$, i.e. the significant wave height of the wave spectrum. This implies that the radiated and scattered waves have diminished and only the incident waves are present.

When comparing the effect of the spreading parameters s , it can be seen that the wave disturbances surrounding the terminator and point absorber WEC arrays are greater when $s = 100$, i.e. when the arrays are subjected to an almost uni-directional sea. However, the opposite is observed for the attenuator WEC array where greater disturbance is noticed when $s = 4$. The difference is attributed to the means of power generation by the different type of WECs. As the attenuator generates power via articulation in two degrees of freedom, there is a greater interaction with the waves approaching from different directions, which is represented by the multi-directional sea when $s = 4$. On the other hand, the terminator WEC pitches to generate energy with respect to the wave oscillation when the wave approaches in a single direction, i.e. $s = 100$, and thus contributes to a lesser disturbance in the wave field. As the terminator and point absorber WECs generate energy via a single degree of freedom, their presence in the uni-directional sea i.e. $s = 100$ will produce greater wave disturbance because of the higher wave energy in the governing direction. It can also be seen that due to the geometry of the terminator WEC that is oriented perpendicular to the wave propagation direction, greater waves are being reflected upstream as compared to their counterparts of the attenuator and point absorber WECs.

Similar observations are also found for the arrays subjected to the JS wave spectrum as presented in Fig. 15. However, due to the higher energy density in the JS wave spectrum as compared to the BS wave spectrum, the $(H_s)_{wf}$ of the wave field downstream the arrays appear to be slightly greater for the former case. The BS and JS wave spectra can be found in Appendix A.

Effect of Oblique Sea

Figure 15 shows the wave fields surrounding the three types of array when subjected to the JS wave spectrum with wave approaching from $\bar{\theta} = 0^\circ$. The wave disturbances surrounding the terminator and point absorber WEC arrays are found to behave in the same manner with respect to the changes in s . However, the opposite trend is found for the WEC array under oblique sea (see Fig. 16) as compared to those presented when $\bar{\theta} = 0^\circ$ (see Fig. 15), where the wave disturbance increases with greater s value, i.e. $s = 100$. For the terminator WEC array under oblique sea, larger wave separation occurs when the wave hits on the terminator WEC array, which in a group behaves like a single floating breakwater. This wave separation phenomena result in a larger wave disturbance downstream as observed in Fig. 16. Similarly for the point absorber WEC array, the group of devices in the array behaves like a single ‘porous square device’ that blocks the propagation of the waves, hence explaining the higher wave elevation along where the wave separation occurs downstream. It is also found from Fig. 16 that the wave attenuates at a slower pace downstream the WEC arrays as compared to their counterparts of the headsea presented in Figs. 14 and 15. This shows a greater interference of diffracted and radiated waves occur between the devices in the array when subjected to an oblique sea condition. For the case of the point absorber WEC, it can be seen that the wave disturbance is the largest at the downstream of the array after the point where the wave separation occurs at the tip of the ‘porous square device’.

5.2.2 Double-peaked Wave Spectrum Multi-Directional Sea

In the investigation of the OH wave spectrum on the wave disturbance upstream and downstream the WEC arrays, the effects of the spreading index s , peak wave period T_p and wave propagation direction $\bar{\theta}$ are studied. Unless otherwise stated, the wind-sea dominated sea state is assumed for the case study where the swell with

$H_{s1} = 4\text{m}$, $T_{p1} = 15\text{s}$, $\bar{\theta}_1 = 45^\circ$ and $\lambda_1 = 1$ is assumed to coincide with the developing sea having $H_{s2} = 3\text{m}$, $T_{p1} = 8\text{s}$, $\bar{\theta}_2 = 0^\circ$ and $\lambda_2 = 2$.

Effect of Spreading Parameter s

The effect of spreading index s and the wave fields surrounding the three different WEC arrays are presented in Fig. 17. The spreading parameters are taken as $s = 4, 15$ and 100 and it is assumed that $s_1 = s_2 = s$ for the OH wave spectrum. As compared to the disturbance of the wave field due to the single-peaked wave spectra as presented in the previous section, the wave height $(H_s)_{wf}$ is significantly higher for the case of the double-peaked wave spectrum presented here. This is due to the higher energy density when two waves coincide with each other and this can be seen clearly in the OH wave spectrum found in Appendix B. The wave disturbance surrounding all three WEC arrays show similar trend with respect to the increase in s where the greatest magnitude of disturbance is observed when $s = 100$, i.e. the uni-directional case. The reason for this has been explained in the discussion for Fig. 16 in which the uni-directional wave corresponds to the highest energy density. Attention is given to the wave disturbance downstream the array for the case when $s = 100$. As such, it is observed that the effect of the oblique wave, i.e. swell approaching from $\bar{\theta}_1 = 45^\circ$, does significantly change the wave field. In fact, it can be seen that the wave disturbance due to the uni-directional sea is significantly larger as compared to their counterparts of the multi-directional sea, i.e. $s = 4$ and 15 , hence emphasizing the significant effect of s in predicting the $(H_s)_{wf}$ of the wave field.

Effect of Peak Wave Period T_p

The effect of the peak wave period T_p on the wave field surrounding the three WEC arrays is presented in Fig. 18. In this case, the spreading parameters are kept to be the same for the developing sea and swell, i.e. $s_1 = s_2 = 4$ whereas the three peak wave periods for the swell are considered, i.e. $T_{p2} = 5\text{s}$, 8s and 12s . It can be

seen from Fig. 18 that a greater disturbance in the wave field is observed when the wave period is small, i.e. $T_{p2} = 5\text{s}$. This is due to the larger wave diffraction and radiation generated when the arrays are subjected to waves of smaller wavelength. As compared to the case when $T_{p2} = 12\text{s}$, the wave disturbance is almost negligible due to the devices oscillating with almost the same phase as the wave orbital motion and thus do not generate much diffracted and radiated waves.

Effect of Wave Propagation Direction $\bar{\theta}$

Figure 19 shows the wave disturbance surrounding the three WEC arrays with three varying wave propagation directions for the developing sea, i.e. $\bar{\theta}_2 = 0^\circ, 30^\circ$ and 45° . The wave propagation direction for the swell is assumed to be fixed at $\bar{\theta}_1 = 45^\circ$ with $s_1 = s_2 = 4$. It can be seen that the intensity of the wave disturbance is almost similar with the changes in the wave propagation direction $\bar{\theta}_2$. This is because the energy density of the OH wave spectrum does not amplify when the swell coincides with the developing sea at different wave directions (see Appendix B). However, when the two waves coincide at the same direction at $\bar{\theta}_1 = \bar{\theta}_2 = 45^\circ$, it generates a greater disturbance to a larger area downstream the WEC arrays in the oblique direction.

Fig. 14. Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber

WEC Arrays under BS Wave Spectrum for Different s . $\bar{\theta} = 0^\circ$.

Fig. 15. Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber

WEC Arrays under JS Wave Spectrum for Different s . $\bar{\theta} = 0^\circ$.

Fig. 16. Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber

WEC Arrays under JS Wave Spectrum for Different s . $\bar{\theta} = 45^\circ$.

Fig. 17. Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber

WEC Arrays under OH Wave Spectrum for Different s .

Fig. 18. Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber

WEC Arrays under OH Wave Spectrum for Different T_{p2} .

Fig. 19. Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber

WEC Arrays under OH Wave Spectrum for Different $\bar{\theta}_2$.

6. Conclusions

The performance of three wave energy converter arrays, each made of a particular type of WECs, i.e. a terminator, an attenuator and a point absorber WECs was successfully investigated. These arrays were subjected to multi-directional seas. The arrays' performance was presented in terms of the q -factor obtained by using a stochastic analysis. It was shown that the use of double-peaked wave spectrum in generating the multi-directional sea affects significantly the performance of the WEC arrays as compared to their counterparts generated by the single-peaked wave spectrum. In addition. The uni-directional seas ($s = 100$) tend to produce a much larger q -factor because of the greater energy density in the single wave component approaching from one direction. These results suggested that the incorrect use of

794 wave spectra in generating the multi-directional sea will over-estimate the
795 hydrodynamic interaction efficiency, i.e. the q -factor.

796 Comparison of the performance of the three types of WEC showed that the q -
797 factor differs in a relatively greater magnitude with respect to the peak wave period
798 as compared to the wave direction, when subjected to multi-directional sea. Also,
799 the q -factor of the terminator and attenuator WEC arrays are greater when the peak
800 wave period is small, i.e. smaller wavelength whereas the effect of the peak wave
801 period on the q -factor of the point absorber WEC is negligibly small.

802 Comparison of the significant wave height of the wave field showed that the
803 wave patterns upstream and downstream of the arrays depends significantly on the
804 type of WECs where the WEC that generates greater diffracted and radiated waves
805 tend to produce greater wave disturbance. Thus, the attenuator WEC generates a
806 greater wave disturbance followed by the terminator and point absorber WEC; and
807 these phenomena are even more obvious when waves approach from the oblique
808 wave direction.

809 Comparison of the wave disturbance due to the single- and double- peak wave
810 spectra revealed that the latter wave spectrum changes the wave field upstream and
811 downstream of the array significantly. It was found that the intensity of the wave
812 disturbance was very much affected by the changes in the wave spreading
813 parameters used in defining the spreading function and encountering wave length
814 (peak wave period) but not much by the variation in wave direction (for the case of
815 multi-directional sea $s = 4$). In general, this depends on the diffracted and radiated
816 waves generated by the WECs where greater wave disturbances are created when
817 the WECs are subjected to smaller wavelength or when two uni-directional waves
818 interfere with each other.

819 The hydrodynamic interaction of the WEC arrays presented here has added
820 values for WEC designers working on optimising the performance of the array. Also,
821 the wave disturbance upstream and downstream of the arrays can be used as a

guideline to coastal engineers in investigating the effect of the presence of the WEC arrays on the environment.

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Table 1. Principal Dimensions and Properties for Terminator, Attenuator and Point Absorber WECs

	Terminator WEC	Attenuator WEC	Point Absorber WEC
Dimensions	Width $a = 26.0$ m	Length $L = 120$ m	Diameter $\phi = 5$ m
	Immersion depth $d = 9.0$ m	Diameter $\phi = 3.75$ m	Immersion depth $d = 0.25$ m
	Thickness $h = 4.0$ m		
Water Depth D	12.5 m	42 m	25 m
Mass M	Not Required	750 Metric-Tonne	4 Metric-Tonne
Mass Moment of Inertia I	9.1455×10^6 kg.m ²	0.73×10^6 kg.m ²	$6,770.8$ kg.m ²
PTO Damping B_{PTO}	16×10^6 N.m.s	*Hinge 1: 1.9×10^6 N.m.s	4,000 N.m.s
		*Hinge 2: 1.2×10^6 N.m.s	
		*Hinge 3: 1.9×10^6 N.m.s	
		(see Figure 1b for hinge location)	

*The PTO damping B_{PTO} is taken to be the same for the pitch and the yaw of the attenuator WEC

Fig. 1 Dimensions for: (a) Terminator WEC (b) Attenuator WEC (c) Point absorber WEC

Fig. 2 Array layout for: (a) Terminator WEC (b) Attenuator WEC (c) Point absorber WEC

Fig. 3 Computational domain for a generic wave energy convertor

Fig. 4 Capture width for Pelamis 1. $D = 42\text{m}$, $\theta = 0^\circ$, $L = 120\text{m}$, $\phi = 3.5\text{m}$, $d = 1.75\text{m}$

Fig. 5 Hydrodynamic coefficients for Seabased WEC. $D = 25\text{m}$, $\theta = 0^\circ$, $\phi = 5\text{m}$, $d = 0.25\text{m}$.

Fig. 6 Comparison of q -factor of point absorber grid layout under different spacing s . $\theta = 0^\circ$

Fig. 7 Comparison of q -factor between point absorber staggered and grid layout. $s_p = 5\phi$, $\theta = 0^\circ$

Fig. 8 Performance of a Single Terminator, Attenuator and Point Absorber WECs under BS, JS and OH Wave Spectra. $s = 4$.

For BS and JS Wave Spectra: $H_S = 3m$. For OH Wave Spectrum: $H_{S1} = 4m, \bar{\theta}_1 = 45^\circ, T_{p1} = 10s, \lambda_1 = 1; H_{S2} = 3m, \lambda_2 = 2$.

Fig. 9 Performance of an Array of Terminator, Attenuator and Point Absorber WECs under BS, JS and OH Wave Spectra. $s = 4$.

For BS and JS Wave Spectra: $H_s = 3m$. For OH Wave Spectrum: $H_{s1} = 4m, \bar{\theta}_1 = 45^\circ, T_{p1} = 10s, \lambda_1 = 1; H_{s2} = 3m, \lambda_2 = 2$.

Fig. 10 Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under BS Wave Spectrum for Different s . $H_s = 3\text{m}$

Fig. 11 Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under JS Wave Spectrum for Different s . $H_s = 3\text{m}$

Note for fixed variables: $H_{s1} = 4m, \bar{\theta}_1 = 45^\circ, T_{p1} = 15s, \lambda_1 = 1; H_{s2} = 3m, \lambda_2 = 2$

Fig. 12 Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under OH Wave Spectrum. $\bar{\theta}_1 = 45^\circ$.

Note for fixed variables: $H_{s1} = 4m, \bar{\theta}_1 = 0^\circ, T_{p1} = 15s, \lambda_1 = 1; H_{s2} = 3m, \lambda_2 = 2$

Fig. 13 Comparison of q -Factor for Terminator, Attenuator and Point Absorber WEC Arrays under OH Wave Spectrum. $\bar{\theta}_1 = 0^\circ$.

Fig. 14 Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber WEC Arrays under BS Wave Spectrum for Different s . $\bar{\theta} = 0^\circ$, $T_p = 8s$.

Fig. 15 Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber WEC Arrays under JS Wave Spectrum for Different s . $\bar{\theta} = 0^\circ$, $T_p = 8s$.

Fig. 16 Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber WEC Arrays under JS Wave Spectrum for Different s . $\bar{\theta} = 45^\circ$, $T_p = 8s$.

Note for fixed variables: $H_{s1} = 4m, T_{p1} = 15s, \bar{\theta}_1 = 45^\circ, \lambda_1 = 1; H_{s2} = 3m, T_{p2} = 8s, \bar{\theta}_2 = 0^\circ, \lambda_2 = 2; s = s_1 = s_2$

Fig. 17 Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber WEC Arrays under OH Spectrum for Different s

Note for fixed variables: $H_{s1} = 4m$, $T_{p1} = 15s$, $\bar{\theta}_1 = 45^\circ$, $\lambda_1 = 1$, $s_1 = 4$; $H_{s2} = 3m$, $\bar{\theta}_2 = 0^\circ$, $\lambda_2 = 2$, $s_2 = 4$

Fig. 18 Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber WEC Arrays under OH Spectrum for Different T_{p2}

Note for fixed variables: $H_{s1} = 4m$, $T_{p1} = 15s$, $\bar{\theta}_1 = 45^\circ$, $\lambda_1 = 1$, $s_1 = 4$; $H_{s2} = 3m$, $T_{p2} = 8s$, $\lambda_2 = 2$, $s_2 = 4$

Fig. 19 Comparison of $(H_s)_{wf}$ for Terminator, Attenuator and Point Absorber WEC Arrays under OH Spectrum for Different $\bar{\theta}_2$

Appendix A. Bretschneider and JONSWAP Wave Spectra used in Figures 14 to 16 ($H_s = 3m, T_p = 8s$)

Appendix B. Ochi-Hubble Wave Spectrum used in Figures 17 to 19

Note: For Figures 17 to 19, take: $H_{s1} = 4m, \lambda_1 = 1$; $H_{s2} = 3m, \lambda_2 = 2$