Nearshore oscillating wave surge converters and the development of Oyster

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Oscillating wave surge converters (OWSCs) are a class of wave power technology that exploits the enhanced horizontal fluid particle movement of waves in the nearshore coastal zone with water depths of 10–20 m. OWSCs predominantly oscillate horizontally in surge as opposed to the majority of wave devices, which oscillate vertically in heave and usually are deployed in deeper water. The characteristics of the nearshore wave resource are described along with the hydrodynamics of OWSCs. The variables in the OWSC design space are discussed together with a presentation of some of their effects on capture width, frequency bandwidth response and power take-off characteristics. There are notable differences between the different OWSCs under development worldwide, and these are highlighted. The final section of the paper describes Aquamarine Power’s 315 kW Oyster 1 prototype, which was deployed at the European Marine Energy Centre in August 2009. Its place in the OWSC design space is described along with the practical experience gained. This has led to the design of Oyster 2, which was deployed in August 2011. It is concluded that nearshore OWSCs are serious contenders in the mix of wave power technologies. The nearshore wave climate has a narrower directional spread than the offshore, the largest waves are filtered out and the exploitable resource is typically only 10–20% less in 10 m depth compared with 50 m depth. Regarding the devices, a key conclusion is that OWSCs such as Oyster primarily respond in the working frequency range to the horizontal fluid acceleration; Oyster is not a drag device responding to horizontal fluid velocity. The hydrodynamics of Oyster is dominated by inertia with added inertia being a very significant contributor. It is unlikely that individual flap modules will exceed 1 MW in installed capacity owing to wave resource, hydrodynamic and economic constraints. Generating stations will be made up of line arrays of flaps with communal secondary power conversion every 5–10 units.

Keywords: wave energy; oscillating wave surge converter; nearshore

1. Introduction

Although patents on wave power conversion technology date back over 200 years, the bulk of research and development in this area has taken place in the last

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One contribution of 18 to a Theo Murphy Meeting Issue ‘The peaks and troughs of wave energy: the dreams and the reality’.
40 years. The focus of much of this work has been and still is on deep water offshore systems mainly relying on power extraction from heave [1–5]. Another significant area of development has been shoreline oscillating water column devices such as the land installed marine powered energy transformer (LIMPET) [6] or low-head hydro systems such as the tapered channel (TAPCHON) [7]. Until recently, wave power extraction from the surge motion of waves in nearshore waters has received relatively little attention. Maybe this is because there is an historic opinion that the nearshore wave power resource is dramatically less than that offshore. It is true that the nearshore gross wave power resource in all directions can be less than half that in water depths of between 50 and 100 m; however, this is very misleading. Folley & Whittaker [8] proposed that the exploitable wave power resource, which is the resource available to commercial wave power converters in wave farms with an economic cap on installed generating capacity, is a more realistic measure. In many nearshore sites, the exploitable resource is often only 10–20% lower than that offshore [9].

In 2002, the wave power research group at Queen’s University Belfast turned its attention towards devices that are predominantly driven by the surge component of the waves. The team described this family of devices as oscillating wave surge converters (OWSCs). With funding from the Engineering and Physical Science Research Council (EPSRC), a 2 year research programme ensued. The study concluded that a flap hinged to the sea bed at its lower edge with the top edge penetrating the water surface was the most promising form of this type of device. In 2005, Aquamarine Power Ltd was formed to commercially develop this system that they named Oyster [10].

Today, a number of different OWSC concepts have been proposed and some are under commercial development. In addition to Oyster, these include WaveRoller [11], bioWAVE [12] and Frond [13]. WaveRoller, unlike Oyster, is a completely submerged flap. Both bioWAVE and Frond are surface-piercing flaps in deeper water and connected to a hinge on the sea bed by a stalk. These four devices occupy different parts of the design space and have remarkably different hydrodynamic characteristics. There are also floating OWSCs such as the ‘Farley Triplate’ [14] and the ‘Langlee’ [15] systems, which are designed for deeper water. Because their performance depends on the dynamics of the support structure, they occupy a very different part of the design space and they will not be considered further in this paper. Similarly, hinged devices with significant change in displacement when they oscillate, which has a large influence on the hydrodynamics, will not be considered. A notable example in this category is the ‘Edinburgh Duck’ [16].

This paper commences with an overview of the nearshore wave resource, including the physical attributes of this environment. This is followed by a description of the hydrodynamics of OWSCs and some of the output from the extensive research programme during the past 8 years is presented. The influence of some of the key design parameters on the hydrodynamic performance of OWSCs is presented. This has led to the development of the Oyster 1 prototype that was deployed at the European Marine Energy Centre (EMEC) off Orkney in 2009. Finally, some thoughts are presented on the future development of this technology and how it might be embodied in Oyster 2.
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2. The nearshore environment

The nearshore environment, defined here as having a water depth of between 10 and 20 m, offers a range of advantages and limitations relative to deeper water locations in the 50–100 m depth range. Consequently, certain technologies are better suited to these particular locations and cannot necessarily be transposed from one water depth to another. For example, the compliant mooring arrangements of freely floating wave energy converters require a minimum water depth to work effectively and so are not generally suitable for shallower water. Conversely, the structural task \[17\] of wave energy converters that react against the sea bed increases dramatically with water depth and so are not generally suitable for deeper water.

\(a\) Definition of the exploitable wave energy resource

As waves travel from the deep ocean to the shoreline, they transform, as the fluid particle motions are affected by the presence of the sea bed. The natural processes of wave shoaling, refraction, diffraction, surf breaking, white capping, sea bed friction and marine currents all modify the wave properties and the power available to a wave farm. Unlike wind farms, wave energy converters will be deployed in lines that might extend tens of kilometres. These lines may follow depth contours, but, in general, will be approximately orthogonal to the mean direction of wave propagation to minimize the number of devices that are in the energy shadow of wave energy converters up-wave. This is different from wind farms because wave energy converters may extract a significant proportion of the incident energy, resulting in an extensive energy shadow (wind turbines only extract a small proportion of the incident energy and so have a small energy shadow because the wind energy resource extends up into the stratosphere). Because of the necessary directional orientation of wave farms, the simple measure of gross annual average wave power density, which includes an un-weighted sum of wave energy from all directions, is an inappropriate measure of the wave energy resource.

Using the gross annual average wave power density misrepresents the resource because it does not discount the contribution of wave energy approaching perpendicular to the orientation of the wave farm, where the capture of an individual wave energy converter is reduced because of the energy shadow of its neighbours. This misrepresentation is compounded where the power capture is determined by multiplying the individual spectral wave power densities by a hydrodynamic response factor multiplied by an average power take-off (PTO) efficiency because the maximum power rating of the wave energy converter is ignored. An even greater misrepresentation is obtained when the average wave power density is simply multiplied by an average device response factor. Unfortunately, it is not uncommon for early stage reviews of wave energy technologies to use these simplified representations. The most obvious deficiencies in these methods are that the directional distribution of the waves and the maximum power plant rating are not accounted for. These deficiencies are significant because they can result in the conclusion that wave energy converters deployed in deeper water are substantially
more productive than those in shallower nearshore waters; however, it can be shown that much of the difference is due to the misrepresentation of the resource.

In development of a more suitable representation of the wave energy resource, the configuration of the wave farm and maximum power rating must be considered. A reasonable measure of the available, or net, wave energy resource is the energy that crosses the line of the wave farm. That is, the wave resource must be directionally resolved and taken across the deployment line of the wave farm. With respect to maximum plant rating and in particular taking proper account of extreme seas, it must be recognized that all wave energy converters will have limited installed generating capacity, which is chosen on the basis of both economics and part load efficiency. The investment in large-capacity PTO plant, which is used for a few per cent of the year, cannot be economically justified. Moreover, power train efficiency at low load factors can be substantially less than those at high load factors. Many of the wave energy converters proposed to date have load factors of between 25 and 40 per cent and therefore they cannot extract the energy from the more energetic seas.

Folley & Whittaker [8] proposed the concept of wave resource evaluation using the ‘average exploitable wave power density’. This is defined as the mean value of the directionally resolved incident wave power density with the largest seas capped to four times the mean value. Thus, the fixed directional orientation of wave farms and limitations of plant rating are recognized.

(b) Nearshore versus offshore

Folley et al. [9] detailed an analysis of the wave resource at EMEC on the west coast of Orkney, and this is summarized here to illustrate the difference in wave resource at different depths and using different calculation methods. The wave resource calculations, shown in figure 1, are for deep offshore 40 km west of Orkney and at the 50 m and the 10 m deep test sites. The average omnidirectional (gross), the directionally resolved (net) and the exploitable wave power densities are shown to illustrate the transformation from gross to exploitable wave energy resource. Although the greatest difference in wave resource, irrespective of
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Figure 2. Comparison of net incident wave power density at the 10 and 50 m deep wave berths.

calculation method, is from deep offshore to 50 m, the more relevant results are those from 50 to 10 m deep. Figure 2 shows the directional net wave power density at 10 m depth plotted against that at 50 m. In the smaller sea states typically less than around 100 kW m$^{-1}$, the reduction at 10 m depth is only 10 per cent less than at 50 m. However, as the seas increase, the reduction increases owing mainly to wave breaking. The high occurrence of the smaller seas is clearly shown by the density of the data points.

Although this analysis of the wave energy resource is indicative, other locations will be different. Differences will arise owing to factors such as the annual variability of the wave climate and the horizontal distance between the 50 m and 10 m depth contours. A highly variable wave climate is likely to have a lower proportion of exploitable wave energy, while a large distance between the 50 and 10 m depth contours is likely to result in a larger reduction in wave energy resource. However, it is possible to conclude when comparing the nearshore wave resource characteristics in the 10–20 m depth range to that at a depth of 50–100 m that at the nearshore site:

— there is less directional spread of longer and medium period waves;
— the largest waves are limited in height owing to wave breaking; and
— the exploitable wave energy resource is not necessarily significantly reduced.

3. The hydrodynamic design of oscillating wave surge converters

OWSCs are single degree of freedom systems, where typically the body motion is rotation about a hinge aligned orthogonally to the direction of wave propagation. Power is extracted by resisting the motion of the body induced by the action of the waves. A significant body of work exists that details the performance of single degree of freedom wave energy converters, for example, Parks [18], Evans [19] and Falnes [20]. In particular, theories based on potential flow models have shown that in the frequency domain, the hydrodynamics can be represented using frequency-dependent wave force, added inertia and damping terms as shown in equation (3.1), where the external loads are approximated using a linear spring

\[ P_{10} = 0.88 P_{50} - 0.00035 P_{50}^2 \]
and damper,

\[ F = [k - (I + I_a)\omega^2 + j(B + A)\omega]X, \] (3.1)

where \( F \) is the complex wave force, \( k \) is the hydrostatic spring stiffness, \( I \) is the OWSC inertia, \( I_a \) is the added inertia, \( A \) is the PTO damping coefficient, \( B \) is the hydrodynamic damping coefficient, \( \omega \) is the wave frequency, \( X \) is the complex OWSC amplitude of motion and \( j \) is the imaginary number, \( j = \sqrt{-1} \).

The power capture, \( P \), can then be calculated using equation (3.2),

\[ P = \frac{1}{2} A \omega^2 |X|^2. \] (3.2)

Assuming for now that the motion is unconstrained and defining the natural frequency, \( \omega_n \), as \( \omega_n^2 = k/(I + I_a) \), the maximum power capture can be shown to be given by equation (3.3),

\[ P = \frac{|F|^2}{4 B + \sqrt{B^2 + (I + I_a)2(\omega_n^2 - \omega^2)^2}}. \] (3.3)

It can be seen from equation (3.3) that the power capture is influenced by four parameters. However, it is well known that the wave force and hydrodynamic damping coefficient are linked by the Haskanid relation (e.g. Falnes [20]), leaving only three independent parameters. The influence of the inertia is of less interest, but it can be seen that the power capture increases with an increase in wave force, \( F \), and at wave frequencies close to the natural frequency (\( \omega_n^2 \approx \omega^2 \)). Unfortunately, it is not possible to define these parameters arbitrarily to maximize the power capture because they are both linked through the OWSC hydrodynamics. To understand how they are linked, each of the parameters is considered independently before looking at potential OWSC configurations that involve compromises in these two key parameters.

To understand the hydrodynamics of the OWSC wave force, it is common to consider the two-dimensional case of the wave force on a vertical wall, which is due to the rate of change in momentum of the water particles as they are reflected. In this idealization, the wave force is in-phase with the horizontal velocity of the wave. However, such a two-dimensional idealization is misleading as the OWSC would have to be several wavelengths wide, which is generally not the case. In the three-dimensional case of a vertical wall of finite width, the wave force is still owing to the change in momentum, but the ability of the water particles to move around the wall must also be considered. It is well known (e.g. Newman [21], p. 301) that when a body is small relative to the wavelength (the long-wave approximation), then the surge wave force will be in-phase with and proportional to the horizontal fluid particle acceleration of the wave, \( \vec{\eta} \). The long-wave approximation also indicates that the wave force, \( F \), is proportional to the sum of the mass of water displaced by the body, \( M \), plus the hydrodynamic added mass, \( M_a \). These relationships are summarized by

\[ F \approx (M + M_a)\vec{\eta}. \] (3.4)

Based on this more fundamental understanding of the wave force, it is useful to consider how the wave force may vary with key design parameters. The first significant design parameter is the water depth. Folley et al. [22] have shown that
as the non-dimensional water depth (defined as the product of the wavenumber and water depth \((kh)\)) decreases, there is an increase in wave force owing to shoaling and associated increase in the horizontal acceleration of the wave, as shown in figure 3.

Another key design parameter is the OWSC width. Figure 4 shows the effect of OWSC width on the wave force for a surface-piercing flap in 12 m water depth. The change in wave torque is related to an increase in added inertia, which itself is associated with the change in accelerations induced on water particles owing to the presence of the OWSC. Although in the two-dimensional limit, the wave force will increase linearly with the OWSC width, the wave force for OWSCs of finite width will increase initially with the square of the width before tending towards the two-dimensional limit; thus, generally, wave force increases more rapidly than OWSC width. The final key design parameter considered for the wave force is the submergence of the OWSC. It has already been noted that the wave force is associated with the induced wave particle accelerations owing to the OWSC. In comparison with a surface-piercing OWSC, the induced wave

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**Figure 3.** Change in surge wave force (relative to deep water surge wave force) with water depth for a floating hemisphere. Solid line, approx.; filled squares, \(h/R = 2\); crosses, \(h/R = 4\); filled circles, \(h/R = 8\).

**Figure 4.** Variation in wave torque with flap width.
particle accelerations owing to a fully submerged OWSC will be smaller, resulting in a reduction in the wave force. Figure 5 shows the rapid reduction in wave torque on an 18 m wide OWSC in 12 m water depth owing to submergence.

The above analysis uses the same assumptions as virtually all publications about wave forces on wave energy converters; however, another source of wave force is the drag force owing to the relative motion of the wave and OWSC. Typically, drag forces are assumed to be proportional to the relative velocity squared and so could dominate at large velocities or where other wave forces are small. Difficulties with determining the drag coefficient, which defines the relationship between the force and velocity squared, together with the nonlinearity of the system, means that calculating the power capture of OWSCs driven by drag forces is difficult. Unlike potential flow models, the wave force will reduce as the body moves owing to a reduction in the relative velocity.

Now consider the natural frequency of an OWSC. In general, this is dependent on the ratio of the OWSC pitch stiffness and the total OWSC rotational inertia, including the added inertia. Assuming that the water plane area has a negligible influence, the OWSC pitch stiffness is dependent on the excess buoyancy and its distance to the OWSC hinge. For OWSCs with the same relative vertical excess buoyancy distribution, this means that the pitch stiffness will increase linearly with the OWSC width and quadratically with the OWSC height. The total OWSC rotational inertia will, in general, increase with OWSC height and width at a rate greater than that of the OWSC pitch stiffness. For the OWSC height, rotational inertia increases with the cube of the distance from the hinge, while for the OWSC width, it is associated with the increase in added inertia. The added inertia increases more rapidly than the OWSC width for the same reason that the OWSC wave force also increases more rapidly: because of the increase in induced water particle accelerations. Thus, in general, the natural frequency of an OWSC will decrease with increasing OWSC height and width as shown in figure 6 for a 2 m thick surface-piercing OWSC.

Having identified the key hydrodynamic parameters of wave force and natural frequency, and related these parameters to some key design parameters, it is possible to consider the potential of a number of different regions of the design space. While the design space is a continuum, it is possible that a number of
regions with local optima exist. These are typically associated with adoption of a particular design principle, either consciously or otherwise. Recognizing that OWSCs can be designed based on different design principles can help explain why different designs exist.

First consider a region of the design space where the OWSC is tuned. For this, initially consider an OWSC that has a natural pitching period of 10s so that it is well tuned to the incident waves for the North Atlantic. Figure 7 shows the relationship required between OWSC width and height to obtain a natural period of 10s for a 2m thick rectangular OWSC, with a constant density of 300 kg m\(^{-3}\) located at a water depth of 12m with the hinge axis 3m above the sea bed. Some examples of these OWSCs are shown in figure 8. It can be seen that the surface-piercing OWSC (flap A) has a width of only 4.4m and that a wider OWSC (flap B) must be submerged to obtain the specified natural frequency. However, these OWSC dimensions required to obtain an appropriate natural frequency mean that the wave force will be small. An associated problem with the small wave force is that the optimum amplitude of motion at resonance is large. Consequently, when motion constraints are included, the increase in power capture owing to

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{Variation in natural pitching period (contour lines) with OWSC height (water depth) and width for a surface-piercing OWSC.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure7.png}
\caption{Variation of OWSC height with width to obtain a natural period of 10s.}
\end{figure}
Figure 8. Three examples of tuned flaps with very different geometries. (Online version in colour.)

Figure 9. Constrained and unconstrained power capture of a submerged 12 m wide flap tuned to be resonant at 10 s. (Wave amplitude is 1 m, maximum rotation is 0.5 radians ($30^\circ$).) Dashed line, unconstrained; solid line, constrained.

tuning is often not evident, as discussed by Folley et al. [22]. This is illustrated in figure 9, where it can be seen that constraining the maximum amplitude of motion to a reasonable value completely eliminates the peak in maximum power capture at the OWSC’s natural frequency.

Thus, in this area of the design space, the requirements for tuning and wave force appear incompatible. That is, to obtain the required natural frequency, the wave force becomes small, this then means that the optimum amplitude of motions are large and so the increase in power capture owing to tuning cannot be exploited owing to motion constraints.

To avoid the problems with motion constraints, the water depth can be increased together with the buoyancy force to maintain the OWSC’s natural frequency (flap C in figure 8). While this would improve the power capture and enable the benefits associated with tuning to be exploited, the modifications come with a set of associated problems. In particular, the increased water depth would increase the structural task significantly, both because of the larger torques and the larger distances over which they must be transmitted. In addition, the increased buoyancy required to obtain the required natural frequency would increase the loads on the anchor significantly. However, it appears to be the only viable solution that exploits the benefits of a tuned wave energy converter.

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A second region of the design space can be defined by ensuring that the OWSC wave force is large. The wave force can be maximized by ensuring that the OWSC is deployed in relatively shallow water, that the OWSC is surface piercing and that it is relatively wide. A possible configuration would be a 2 m thick, 18 m wide rectangular OWSC deployed in 12 m of water depth. With a constant density of 300 kg m$^{-3}$, this configuration has a natural period of around 20 s, well outside the incident wave frequencies. However, although the theoretical maximum power capture cannot be achieved in this configuration because it is not optimally tuned, the capture factor remains high. Both numerical and physical models of this configuration have obtained capture factors over 0.7 in irregular waves, with an average capture factor for a wave climate of around 0.5. Thus, although the configuration is sub-optimal, the power capture remains significant.

An additional, interesting, region of the design space emerges if the OWSC width is increased to about 50 m and the thickness to about 5 m. In this region, it is possible to obtain multiple natural frequencies of the OWSC covering the full range of incident wave frequencies, as illustrated in figure 10. These multiple natural frequencies occur because the added inertia is frequency dependent, allowing multiple solutions for the natural frequency. Physically, the variation in added inertia occurs because of displacement of the local water surface with flap rotation. This effect can also be deduced from the oscillatory nature of the impulse response function, which at frequencies close to the frequency of the impulse response function’s oscillation results in very low torques in-phase with flap rotational acceleration. Numerical models of this configuration indicate that it should be possible to capture very nearly (greater than 99%) the maximum theoretical power capture for this device width (which is greater than for an idealized surging point absorber owing to the finite device width) across the whole frequency range without the need for any reactive energy control. In addition, the large wave forces for such a wide OWSC mean that motion constraints are typically not an issue. However, although the maximum theoretical power capture is nearly possible, the capture factor is less than for the untuned OWSC with half the width. This occurs because the maximum capture

Figure 10. Reactive force coefficients versus wave period (50 m wide flap) shows multiple resonances as the inertial force equals the spring force. Solid line, inertia; dashed line, stiffness.

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factor of the wider OWSC is beginning to be affected by the two-dimensional limit of 0.5, while the maximum capture factor of a narrower OWSC is more influenced by the point absorber effect, which enables the capture factor to be greater than 1.

The final region of the design space to be considered is defined by the wave force being dominated by drag. To maximize this force, the OWSC should be deployed in relatively shallow water to increase the horizontal motions of the waves. An OWSC driven by drag will have relatively small motions because they will always be less than the horizontal motions of the waves. Although it is possible for drag forces to dominate in large bodies, it is likely that OWSCs in this region will be relatively small with relatively small power captures.

These design space regions are not meant to be exclusive or exhaustive and clearly alternatives exist. However, they do illustrate that different locally optimal designs may exist and depend on how the OWSC is envisioned to operate. It is possible to see how the designs of the current OWSC concepts being commercially developed can be placed in different regions of the design space, although it is generally unclear how conscious the developers are of the choices that they have made and how they have optimized their designs.

4. The development of Oyster

(a) Design philosophy

When designing a wave energy convertor, in addition to understanding the different hydrodynamic regions of the design space, there are a range of fundamental principles that should be adhered to if cost-effective reliable machines are to evolve. The biggest challenge is how to extract energy economically from a highly variable resource, which has extremes several orders of magnitude greater than the mean and without resorting to substantial structures that are redundant for most of the time. This design philosophy was originally proposed by Whittaker & Folley [23]; the ideal characteristics identified are summarized below:

(1) a wide bandwidth response so that capture width is maintained over the working frequency range instead of being highly tuned to a particular frequency;
(2) a progressive decoupling from the incident wave excitation as the wave height increases so that in extreme seas, the capture efficiency is very low, thus, a relatively modest installed capacity can cope with the power conversion;
(3) high structural efficiency ensured by the shortest load paths from the wave excitation force through the PTO system into the reaction platform;
(4) a machine in which all elements are essential to the power conversion process with minimal redundancy, except where duplication is deemed necessary to maintain reliability; and
(5) a ‘plug and play’ approach to PTO sub-assemblies, which are most prone to failure.
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(b) Oyster 1

The conclusion from the EPSRC-funded research programme [24] was that the simplest type of device that meets these criteria is a flap structure with its bottom edge hinged to the sea bed. As it rotates to larger angles, the vertical projected frontal area reduces, giving progressive decoupling as the wave force increases (characteristic 2). The sea bed provides the frame of reference and avoids the need for a dynamic reaction, which adds complexity to the system (characteristic 4). Although attaching to the sea bed is the most difficult part of the operation, it results in a stream of advantages such as the avoidance of flexible power transmission connections and allows tight geometric spacing of units within the wave farm, thus maximizing the extraction of the wave resource over a given sea bed footprint. The solid framework means that a ‘plug and play’ approach is more easily achieved (characteristic 5).

Refining the optimum OWSC design further, then the design space of most promise is that where the wave force is maximized. It has been shown above that this region of the design space has a broad bandwidth response (characteristic 1) and relatively short load paths (characteristic 3). Conversely, the design space for tuned OWSCs will almost certainly, by definition, have a narrower bandwidth (contravening characteristic 1) and/or longer load paths (contravening characteristic 3), which were shown to be necessary to exploit the benefits of the tuning. An OWSC driven by drag forces will experience larger forces as the waves get bigger owing to the quadratic relationship of the force with water velocity (contravening characteristic 2), although wave force decoupling at large angles may reduce this effect. The final region of the design space identified above is that containing the multi-resonant OWSCs. While this region also satisfies characteristics 1 and 3, the capture factor is typically smaller. Thus, although the design space should not be discarded, it is sensible to first focus on the region of the design space where wave force is maximized.

Having identified a region of the design space, the first consideration is water depth. Being a surging device, it is essential to tap the amplified horizontal fluid particle motion as a wave climate shoals in shallow water. However, figure 11 shows that below around 10 m depth, an ocean wave with an average period of 10 s and a significant wave height of 4 m will lose a significant proportion of its power owing to breaking. A significant wave height of 4 m or less represents the vast majority of sea states that occur along the western seaboard of the North Atlantic. Taking a target tidal range of 4 m or less, a nominal mean water depth of 12 m was chosen for Oyster 1 and continues to be the preferred depth for Oyster 2.

An extensive research programme comprising a combination of physical and mathematical modelling has been undertaken at Queen’s University to determine the relationship between the physical dimensions of the flap, its dynamic characteristics, the PTO damping characteristics and power conversion in a wide range of seas [25]. Figure 12 shows an example of effect of flap width on capture factor in a range of sea states with different energy periods (Te) and power flux (P). In all but the shortest period waves, the capture factor increases with increasing flap width, shown here from 9 to 36 m. The reduction in capture factor for the 36 m wide flap at Te of 7 s is a result of the high width to wavelength ratio that results in the flap starting to behave as a two-dimensional device, which ultimately limits the capture factor to 0.5. This also
indicates that there will be a limit to the performance enhancement of flap width, with even wider flaps only gaining in the longer period seas and losing in the shorter ones. A second observation is that performance reduces as the sea power increases for a given energy period, demonstrating the OWSC’s ability to progressively decouple. It should be noted that the capture factors presented in this figure are indicative of what can be achieved, but can be increased or decreased depending on factors such as flap thickness, freeboard, pitch stiffness and damping torque characteristics.

However, the cost of power cannot be minimized by optimizing hydrodynamic performance alone. Another key factor for sea bed reacting devices is foundation loads. Unfortunately, increases in power output per flap are accompanied by increases in both surge and heave loads on the sea bed connections.
Figures 13 and 14 show how surge and heave loads, together with average hydraulic power in a weighted range of seas can be significantly changed by flap width, pitch stiffness (high, HPS; medium, MPS; low, LPS) and water depth. Again, these results are only indicative and can be varied significantly by flap shape and damping characteristic.

The above presentation gives a very small sample of the interplay between the many variables that govern the performance and cost of OWSC devices. Sea bed hinged flaps might seem to be the simplest of wave power converters; however, their design optimization, even from a purely hydrodynamic viewpoint is challenging. Then, it must be remembered that the hydrodynamics is only one part of the optimization process that includes structure, secondary power conversion and transmission, installation and finally maintenance.

(c) The deployment of Oyster 1

The general basis of design for Oyster 1 was fixed in 2007 and much of the work reported above has been conducted since then. Aquamarine Power successfully
installed the Oyster 1 full-scale proof-of-concept device at EMEC in Orkney in the summer of 2009 and used it to inform the design of Oyster 2, which was installed in the summer of 2011.

Oyster 1 is basically a wave-powered pump driving water at high pressure through pipelines to a high-head hydroelectric plant onshore. The general layout of Oyster 1 is shown in the schematic of figure 15.

The flap structure and general arrangement of the offshore PTO components are shown in figure 16. The body of the flap was constructed from five 1.8 m diameter steel tubes. The 18 m wide, 11 m high flap was secured to the sea bed by drilled and grouted piles in a connector frame. A general view of the onshore hydroelectric plant is shown in figure 17. The container with open doors houses the Pelton wheel, flywheel and generator. The container to the left houses the electrical power converters and computer monitoring systems.

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(d) Offshore power take-off components

The wave-induced movement of the flap is converted into pressurized water hydraulic energy using two double-acting hydraulic cylinders mounted between the flap itself and the base frame structure. The flap’s resistance to motion, or damping torque, is determined by the internal area of the two cylinders, the lever arm that governs stroke and the water pressure. The device does not use any continuous ‘wave-by-wave’ control of the damping torque, but energy capture can be optimized by slowly adjusting the system target pressure at the onshore hydroelectric plant, which changes the damping torque. High-pressure water is transmitted to the onshore hydroelectric plant through conventional directionally drilled pipelines. A closed loop is used, which has been found to be more economically and technically attractive than pumping sea water because it avoids the challenges of offshore filtration, corrosion, bio-fouling and location of the discharge piping.

(e) Onshore hydroelectric plant

The onshore hydroelectric plant comprises largely standard components combined and controlled in a novel manner. The power plant uses a variable speed induction generator coupled with a Pelton wheel turbine and flywheel. The flywheel is the primary source of energy storage in the Oyster power train and acts to smooth out the delivered power over a wave cycle and significantly reduces the required generator capacity. A relatively simple control system operates the plant efficiently and safely. The system pressure is regulated by the spear valves that control the flow of high-pressure water onto the Pelton wheel. They are adjusted continuously to keep the average operating pressure in the system as close as possible to the optimum target pressure for the sea state, while simultaneously...
keeping the ratio of the spear valve nozzle velocity and the Pelton wheel bucket speed close to its optimal value. The response time of the spear valves must be sufficiently fast to limit pressure fluctuations during each wave cycle. Changes in target pressure occur over much longer time frames according to changes in the incident wave climate. The final regulation of the variable speed generator output is by a power convertor/electronics that provide the necessary full rectification and inversion before a step-up transformer supplies power to the grid.

Following commissioning, the device produced first power in October 2009 and provided invaluable operational data regarding device performance and loading, which is being used for numerical and wave-tank model calibrations and refinements. It was decommissioned in 2011 when Oyster 2 was installed. Aquamarine Power has gained a phenomenal amount of knowledge regarding the design, construction, installation, maintenance and operation of this type of system. The sea trials to date have shown that power conversion and delivery to the grid using an OWSC is technically possible. As can be expected with any new technology, even with one using mainly ‘off the shelf’ components, there are technical challenges with some components in the PTO system. Parts have had to be redesigned, manufactured and retrofitted. With Oyster 1, it was decided early in the design process to undertake component maintenance in situ rather than detach the flap from its sea bed frame and take it to harbour.

This has been possible because of one of the most important features of Oyster: the ability to water ballast the flap and sink it onto its base frame where it is latched. For health and safety reasons, this is an essential requirement for diver maintenance and inspection. In its first year of sea trials, Oyster 1 has survived very severe wave conditions in both the operational and locked down positions. It is the only wave power device in the world that has been deliberately sunk several times in a fully controlled manner for maintenance. Component refinement and replacement was ongoing during the operational period, and was an essential part of this sea trial.

5. Conclusions

The deployment of Oyster 1 at EMEC is a world first in the sense that previously nobody had ever fixed a mobile machine of this size to the sea bed in shallow coastal waters. Its first year of operation at sea has shown that it is technically possible to convert ocean wave power into electrical energy delivered to a national grid. Consequently, OWSCs located in the shallow nearshore region with depths as low as 10 m are serious contenders in the challenge to produce economic, reliable power from ocean waves. This conclusion is supported by the following:

— the exploitable nearshore wave resource at a nominal depth of 10 m is only 10–20% lower than that at 50 m for sites with a 1 : 50 bed slope;
— for surging devices located in the nearshore region, this is offset by exploitation of the amplified horizontal wave-induced fluid motion owing to shoaling, the reduced directional spread in the seas and filtering out of the extreme seas owing to breaking;
— devices such as Oyster are point absorbers that primarily respond to the horizontal fluid acceleration in the working frequency range, Oyster is not a drag device responding to horizontal fluid velocity;
— it had been found that resonant OWSCs do not realize their theoretical potential owing to the motion constraints of ‘real’ devices and consequently do not meet the set of optimal design criteria that have been proposed;
— Oyster is a full-depth flap from above the water surface to the sea bed. It is not resonant in the working frequency range and maximizes the wave excitation force, while maintaining an acceptable angular velocity to limit vortex losses at the edges;
— OWSCs have a natural survival characteristic in that they progressively decouple from waves as they become larger and the flap oscillation angles from the vertical increase;
— one of the most important features of Oyster has proved to be the ability to water ballast the flap to sink it onto its base frame, where it is locked to enable safe diver access for maintenance; and
— OWSCs cannot be optimized on hydrodynamics alone, structure, secondary power conversion and transmission, installation and finally maintenance over decades must be considered to develop cost-effective reliable wave power converters.

This has been a phenomenal journey from the initial thoughts discussed at coffee in 2001 through the initial EPSRC grant that funded the initial research, the formation of Aquamarine Power Ltd by Allan Thompson in 2005 to develop the Oyster concept, the deployment of the 315 kW Oyster 1 at EMEC in 2009 and now the deployment of Oyster 2. Hundreds of people have been involved. However, none of this would have been possible without very substantial funding from both the public, but mainly the private sectors. The final acknowledgement must go the late Prof. Alan Wells FRS, who founded the wave power group at Queen’s University in the mid 1970s and devoted much of the last 30 years of his life to the development of wave power technology.

References


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