Design of the Next Generation of the Oyster Wave Energy Converter

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Abstract

This paper discusses some of the key design drivers for the next generation of the Oyster wave energy converter which is being developed by Aquamarine Power Ltd. The paper presents a general overview of the Oyster technology including the nearshore wave energy resource, the power capture characteristics of bottom-hinged flap type oscillators and the hydroelectric power take-off system. A status update is then provided for the full-scale proof of concept device which was successfully installed at the European Marine Energy Centre (EMEC) in Orkney, Scotland in 2009. The final section, and main body of the paper, concerns the next generation of Oyster device, Oyster 2, which is currently being developed for deployment in 2011. The paper provides an introduction to the fundamental tenets which have guided the design as well as an overview of the ensuing features and the resultant step-change improvement in the performance of the device.

Keywords: Nearshore wave energy, Oyster, Aquamarine Power.

1. Introduction

In response to the need to find additional sources of renewable energy to combat climate change, ensure domestic energy security and develop new industries a large community of wave energy researchers and commercial device developers has arisen in recent years, pursuing a considerable number of different technologies for the conversion of wave energy. The focus has often been placed on devices situated offshore, in deeper waters, due to the perceived advantage of the higher gross energy levels encountered there. However there are a number of commonly overlooked advantages associated with the nearshore environment that make it a preferable wave climate for an appropriately designed wave energy converter (WEC).

Aquamarine Power Ltd was formed in 2005 to develop Oyster, a WEC that interacts efficiently with the dominant surge forces encountered in the nearshore wave climate at depths of 10 to 15 m. The Oyster concept utilises a wide buoyant bottom-hinged oscillator (or flap) that completely penetrates the water column from above the surface to the seabed [1]. The wave force on the oscillator, from the surging action of waves, drives hydraulic pistons that pressurise water and pump it to shore through pipelines. The onshore hydroelectric plant converts the hydraulic pressure into electrical power via a Pelton wheel, which turns an electrical generator. The water passes back to the device in a closed loop via a second low pressure return pipeline.

Aquamarine Power successfully installed a 315kW full scale proof of concept device at the European Marine Energy Centre (EMEC) in Orkney, Scotland, in the summer of 2009. Following final connection and commissioning, first power was achieved in October 2009. The project, named Oyster 1, has been producing valuable performance and loading data which will be the focus of a future publication.

An extensive set of tank tests and numerical modelling is being carried out with Queen's University Belfast in order to refine the next generation of Oyster device. The results of this fundamental research, together with the experience gained during the design, deployment and condition monitoring of Oyster 1, have dictated the nature of the next 'Oyster 2' device. This new design contains numerous performance enhancements which will place the technology within close reach of a commercial launch. Oyster 2 comprises three next-generation offshore wave capture units with a total generation capacity in excess of 2 MW. A successful demonstration project at this scale is required to prove the technology reducing technical and operational risks

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associated with large-scale deployments to a level which is commercially attractive to mainstream investors. Oyster 2 is currently in the detailed design phase and will be installed at EMEC in summer 2011.

This paper begins with a discussion of the basic principles governing the Oyster technology; in particular the nature of the nearshore wave resource, the hinged oscillator and the hydroelectric power take-off. The paper then gives a brief update on the status of the successfully installed Oyster 1 project before providing a more detailed examination of the governing philosophies behind the development and key design features of Oyster 2.

2. Basics of the Oyster Concept

The Oyster concept is a unique design of WEC due to its nearshore location, the use of a bottom hinged flap that completely penetrates the water column, and an onshore hydroelectric power take-off (PTO). This section discusses the benefits associated with each of these aspects of the technology.

2.1 The Nearshore Resource

The relatively low number of WECs designed to operate in the nearshore region (typically defined as being 10 to 25 m in depth) could be attributed to the perception of low energy levels in shallow water depths. However it is argued here that any such perception is largely untrue and ignores many of the benefits associated with the nearshore resource.

2.1 (a) Gross versus Exploitable Resource

While the levels of gross omnidirectional power do, indeed, differ significantly between the offshore and nearshore, to use such a simple measure to characterise the resource would be misleading. It is important to compare the two regions with an appropriate measure of available energy that can account for the real-world limitations of WECs and arrays of WECs.

Any individual WEC has a rated power that is reached for a given set of design wave conditions and which is set by economic considerations. Further increases in incident wave energy cannot produce a further increase in power output and the excess energy is either spilt or the device goes into a protective shutdown. This lost energy must be excluded from any calculation of resource levels to allow a representative comparison. Also, the consideration of the directionality of a wave resource is important. An omnidirectional description of wave power is suitable when discussing a single point absorber, but the directionally resolved power can provide a more appropriate measure when considering a typical array/farm of such devices (or indeed any design of WEC) in a row orthogonal to the mean direction of wave propagation [2].

Folley & Whittaker [2] introduce the concept of measuring the resource using the average exploitable wave power which is defined by the average wave power propagating in a fixed direction for a single sea-state and limited to a multiple of four times the annual average wave power. The deep water region, with its larger directional distribution and higher proportion of extremely energetic sea states, is ‘cropped’ significantly by such a measure of the resource; more of the energy is effectively unusable by a WEC. In the nearshore, where refraction has tightened the directional spread and wave breaking has reduced the proportion of highly energetic seas, the proportion of energy that is unexploitable is lower. Folley et al. [3] calculate both gross omnidirectional and exploitable wave powers for EMEC and show (Figure 1) that the gross power offshore is twice that in the nearshore, but there is only a 10 percent difference between the exploitable power at the offshore and nearshore locations.

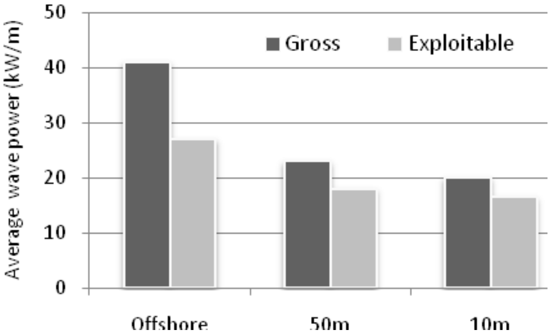

Figure 1: Average gross and exploitable wave power at three water depths (50m and 10m correspond to ‘deep-water’ and ‘nearshore’ respectively) at EMEC [3].

This means that the difference between the deep-water and nearshore resource levels is much less than a basic analysis of the wave climate suggests; thus nearshore WECs can be exposed to almost the same levels of exploitable energy as their deep water counterparts.

2.1 (b) Extreme Waves in the Nearshore

For Oyster, this small decrease in exploitable wave energy is compensated by the lower extreme loads encountered in the nearshore. Storm events produce wave conditions far beyond the normal operating regime and demand a corresponding level of structural integrity (and thus cost) in excess of that required for normal operation.

In the nearshore, the energy losses associated with the phenomena of wave breaking and seabed friction are beneficial in reducing the peak wave heights encountered by the device. These two loss mechanisms naturally filter out the extreme wave events but have less effect on the more commonly occurring sea states [4]. This means that Oyster gains a large degree of inherent storm protection without sacrificing much in the way of exploitable wave resource. Table 1 gives the results of modelling this filtering effect for four storms off the coast of Ireland and shows the considerable diminishment in wave height at the 12 m contour.

Water depth	Storm 1 17/02/97	Storm 2 27/02/98	Storm 3 27/12/98	Storm 4 09/02/00
12 m	6.9	6.8	7.8	8.7
50 m	10.4	15.6	13.3	14.8
110 m	18.0	17.7	17.4	18.1

Table 1: Maximum modelled wave heights (m) off the coast of Donegal in Ireland during four major storms [4]

In conclusion, the nearshore resource is almost as powerful as, but without the harmful extremes of, the offshore resource.

2.2 The Flap Concept

WECs such as Oyster extract energy from the surge motion of the waves. This surge motion is amplified in shallow water due to the shoaling effect induced as the wave travels over the gradient of the seabed. For a bottom-hinged seabed mounted flap, Folley et al. [5] have shown that the maximum power capture depends primarily on the incident wave force (or ‘wave torque’ for an angular oscillation) rather than the incident wave power. As a result they conclude that, in general, the increase in wave force (and thus power capture) as waves progress to shallower depths more than compensates for the relatively minor loss in wave energy due to seabed friction and wave breaking. This leads the designer to place Oyster as close to shore as possible while respecting the significant drop in wave energy that occurs at very small depths due to excessive wave breaking (Figure 2).

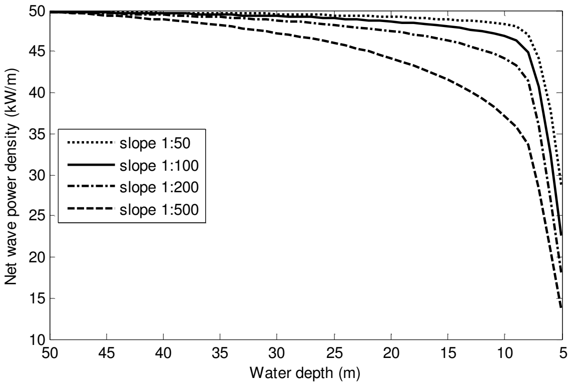

Figure 2: Reduction in net wave power with water depth over various bed slopes [2]

Three further factors have been shown to maximise power capture [6]. Firstly, widening the flap amplifies the wave force, which increases approximately proportionally to the width squared. Secondly, the flap should be surface piercing and block the full height of the water column to ensure that the wave force generated is maximised. Experiments undertaken at Queen’s University Belfast [7] have shown that leakage under or through the flap can result in a power loss of up to 30 percent. Thirdly, to maximise the wave torque, the hinge point should be located as close to the sea bed as possible to increase both the working surface of the flap and the moment arm from the hinge to the centre of pressure.

A further benefit is the naturally broad bandwidth response of a pitching device. It is found [6] that, *“because the natural pitching period of the device [Oyster] is typically much greater than the incident wave period, tuning has a minimal influence on performance”*. Performance can remain high for a wide range of incident sea-states without having to resort to the continuous phase control strategies that many other WECs employ to try to achieve good energy capture efficiencies. Oyster is controlled in a basic fashion onshore by maintaining a design pressure in the system through the regulation of the water flow in the hydroelectric plant (Section 2.3(c)). This eliminates a large degree of complexity and cost from the control system and has important implications for offshore device maintenance.

Oyster has its highest capture efficiencies in the more frequently occurring sea state of low wave height. As the wave heights, and periods, increase towards large seas Oyster naturally decouples from the waves, giving a good load factor. This also provides the inherently self-protecting nature of the design. Extensive wave tank modelling has shown that the flap ‘ducks’ under the largest storm waves. The oscillating flap only experiences 25% of the loading that an equivalent vertical rigid structure would experience.

2.3 Oyster Power Train Concept

As the wave industry continues to mature, there is a growing recognition of the importance and challenges of the secondary power take-off system. Reliability, maintainability, efficiency and achieving response times demanded by control philosophies at full scale all present significant challenges.

The close proximity to land and broad bandwidth response [6] permit efficient hydraulic power transmission to shore and avoid any need for control equipment in the offshore environment. The electrical systems can be situated onshore with the corresponding benefits of reduced offshore complexity, ease of access for maintenance and reduced cost through the use of standard onshore components. Table 2 shows the average distance from shore to the 13 m contour for a range for potential target markets in Ireland and Scotland.

Location	Average distance to shore
Orkney Islands	500 m
Shetland Islands	250 m
Lewis	700 m
Uist	3300 m
Irish Coast (North West)	500 m
Irish Coast (West)	1000 m

Table 2: Average distance to the shoreline from the 13m water depth contour (typical Oyster installation depth) for a number of suitable deployment sites.

Careful location of the offshore devices and the hydroelectric plant provides scope to further reduce the distance between the components. An average project could expect to have a distance to shore of around 500 m.

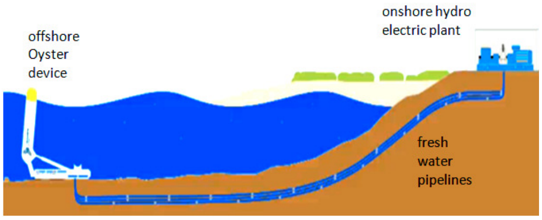

Figure 3: General outline of the Oyster concept.

2.3 (a) Offshore Power Take-Off Components

Kinetic energy of the moving flap is converted into hydraulic energy using double-acting hydraulic cylinders to pressurise water. Each Oyster device uses two such 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, their mounting eccentricity and the fluid operating pressure. As mentioned earlier, the device does not require any continuous 'wave-by-wave' control of the damping torque, but the energy capture can be increased by optimising the damping torque by slowly adjusting the system target pressure at the onshore hydroelectric plant.

2.3 (b) Power Transmission to Shore

High pressure water is transmitted to the onshore hydroelectric plant through conventional directionally drilled pipelines. A closed loop is more economically and technically attractive than pumping sea water and avoids the challenges of offshore filtration, corrosion, bio-fouling and outlet piping.

Deployments of farms of Oyster units will have a number of offshore devices connected to a common offshore manifold and sharing a set of pipelines back to the hydroelectric plant onshore. The array of offshore devices would subsequently be working at a common pressure; however high efficiencies of power capture would be retained as the individual devices do not need continuous wave by wave control.

2.3 (c) Onshore Hydroelectric Plant

The onshore hydroelectric plant comprises largely standard components, albeit combined and controlled in a novel manner. The concept uses a variable speed induction generator coupled on a shaft with a Pelton wheel turbine and a flywheel. Deployment of a number of devices in an array serves to smooth the power fluctuations presented to the hydroelectric station; however considerable power variation can remain that must be dealt with. 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 reduce the required generator capacity.

A relatively simple and innovative control system operates the plant efficiently and safely. The system regulates many PTO variables; however, paramount of these is the operation of the spear valves that control the flow of high pressure water onto the Pelton wheel. The spear valve control has two distinct objectives; firstly to keep the average operating pressure in the system as close as possible to the optimum target pressure for the sea state, and secondly, to keep 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 is relatively fast in order to control 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 power converters/electronics that provide the necessary full rectification and inversion before a step up transformer supplies power to grid.

Figure 4 shows the operational Oyster 1 onshore power take-off compound close to completion of construction. The container in the foreground houses the Pelton wheel and generator. The container behind it houses the power converters.

Figure 4: Oyster 1 onshore power station at EMEC

3. Oyster 1 Update

The Oyster technology concept described in the previous section reached a major milestone when Aquamarine Power successfully installed the Oyster 1 full scale proof-of-concept device at EMEC in Orkney in summer of 2009. The device is located in 13 m of water. The flap is 18 m wide by 11 m high and secured to the sea bed by drilled and grouted piles in a connector frame. Figure 5 shows a graphical representation of the device.

Figure 5: The offshore Oyster 1 device.

The body of the flap is constructed from five 1.8 m diameter steel tubes. The power take-off cylinders are mounted at the quarter points of the flap and the non-return valves are housed in the sub-frame. Hydraulic power is transmitted to shore via directionally drilled pipelines and converted to electrical power and exported to the grid by a 315 kW rated hydroelectric plant with associated power electronics. Figure 6 shows the device being readied for transport to EMEC while Figure 7 shows the flap and sub-frame being lowered onto the foundation frame at the deployment site.

Figure 6: Load-out of Oyster 1 for transport to EMEC

Figure 7: Deployment of the Oyster 1 device at EMEC. Jack-up barge remains after drilling and pile insertion

Following commissioning, the device produced first power on the 16th of October and continues to providing invaluable operational data regarding device performance and loading which are used for model calibration. Figure 8 illustrates a comparison of tank test results and in-house mathematical models against Oyster 1 operational data. Note that negative rotation relates to the flap's angle from vertical in the seaward direction.

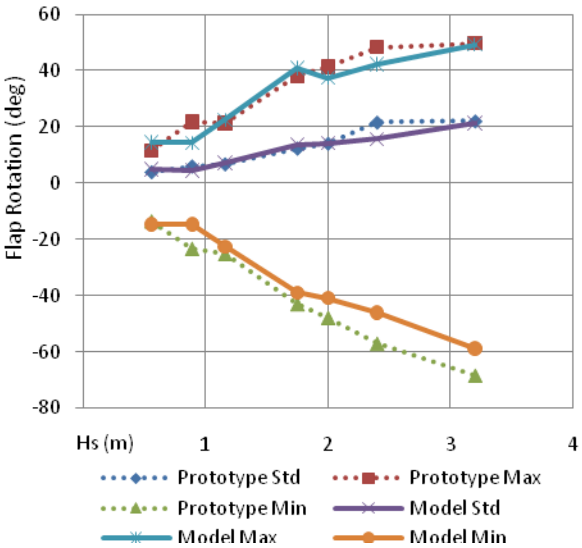

Figure 8: Example of verification of hydrodynamic model results using Oyster 1 prototype data

4. Oyster 2 Design Process

The successful deployment and operation of a full scale WEC in the high energy seas of Orkney was an important demonstration of the viability of the Oyster technology. The next evolution of device will build on the learning from the first generation design and make important performance and cost improvements. The Oyster 2 project is a three oscillator, 2.4 MW project scheduled to commence installation in summer 2011. Oyster 2 retains the fundamental concept of operation from Oyster 1 but is a significant improvement in both scale and design. Oyster 2 exploits the recent innovations and improvements resulting from the ongoing programme of research at Queen's University Belfast.

This section of the paper describes some of the key objectives, constraints and design decisions in the Oyster 2 design.

4.1 Key Design Objectives

Marine renewable energy devices, like all devices in the energy supply sector are ultimately judged by their delivered cost of energy over their operational life. This is the key consideration in terms of device design; however the delivered cost of energy can be difficult to use as a practical design metric due the large number of dependent factors. Numerous contributors to delivered energy cost were considered during the concept design process. The three found to have the largest impact are average power output, device availability and installed device cost

4.2 Design Variables

There are a large number of design variables for a device such as Oyster. Only a subset of the fundamental device characteristics are discussed here.

4.2 (a) Oscillator Dimensions and Shape

A large program of 40th scale testing was undertaken in Queen's University Belfast to consider variations in flap shape and properties. These results will be more fully presented in future publications and are summarised here. Key oscillator design variables include:

Flap Width – the width of the device is the dimension along the crest of the incident waves. The added mass moment experienced by the flap, which is advantageous for energy production, increases nonlinearly with increasing flap width; wider flaps capture more power in proportion to their size, improving their capture efficiency. Three considerations provide an upper limit to the flap width. Firstly, wider flaps experience increased structural loading and require a higher level of damping torque, both of which increase structural cost. Secondly, the capture efficiency of extremely wide flaps diminishes as the flap width becomes a significant portion of the incident wavelength and the terminator effect dominates [4]. Finally, for very wide flaps performance is degraded in non-orthogonal seas due to the phase variation of the wave force acting across the width of the device.

Pitch Stiffness – the pitch stiffness of the flap is a measure of the tendency of the flap to right itself due to buoyancy. Increasing the pitch stiffness of the design has been shown to improve power capture in experiments, but this comes at the expense of increased extreme structural loads during storm conditions.

Freeboard – the freeboard describes the height of the flap that extends above the mean water level. Within bounds, increasing the freeboard reduces power losses due to wave overtopping of the device and therefore improves capture efficiency.

End Shape – an oscillating Oyster flap loses energy due to viscous effects as a result of the relative velocity between flap and fluid. Tank tests were undertaken to determine if these losses could be reduced by modifying the edge profiles of the flap. Some of the configurations tested are shown in Figure 9 below.

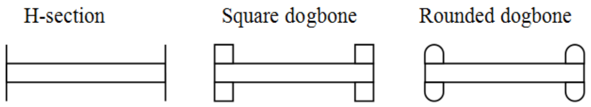

Figure 9: Different categories of end profile

Results show that the flaps with wide rounded ends minimised energy losses and therefore increased power capture. The exact magnitude of the benefits of the end effectors at full scale is difficult to infer reliably from model tests; however it is likely that wide rounded end effectors on the flap have a significant positive contribution.

4.2 (b) Structural Configuration

In terms of structural integrity, both extreme storm and fatigue loading conditions drive the design of the flap, baseframe and foundations. A typical Oyster device experiences around 4 million reversing load cycles per year, while storm events can cause loads many times higher than those experienced during normal operation. The overall philosophy for load transfer and location of hinge and bearing points are key design decisions. The changing wave force, as represented by a pressure distribution across the flap (Figure 10), must be converted by the hydraulic power take-off system and the resultant loads must, in turn, react against the main bearings and structure to transmit through the foundation to the seabed.

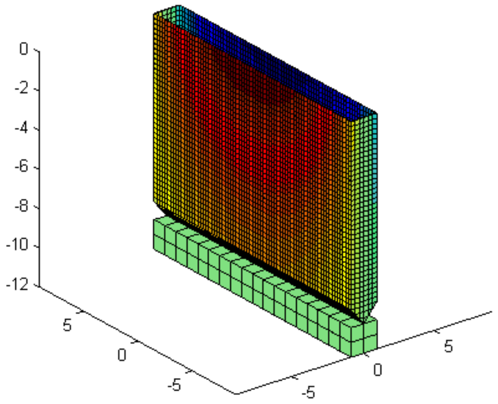

Figure 10: Example of the radiation pressure distribution across an 18 m wide flap as modelled in WAMIT® in response to a 2 m wave with 9 second period.

Furthermore, key decisions regarding the flap construction, location of the main bearings, design of the cylinder mounting arrangements and baseframe have to consider the structural issues as well as the requirements and practicalities of installation and maintenance.

The structural integrity of the flap, baseframe and foundations is primarily governed by fatigue loading. The magnitude of the fatigue loading is partly controlled by the operation of the device. The response characteristics of the flap are designed to change for different prevalent sea states. The control of the damping torque via the system pressure was introduced in Section 2.3(c); it plays an important role in determining the fatigue life of the device and also the pressure ratings of the hydraulics. A large range of damping torque (hydraulic pressure) can introduce considerable cost into the system through a stronger supporting structure, longer torque arms, longer cylinder stroke lengths, heavier duty cylinders to avoid rod buckling and the knock-on effects of increased loads on other components. It is therefore useful to regulate the damping torque relatively closely around its average optimum value. The resulting benefits for fatigue loading and pressure rating comes at the expense of power capture, but fortunately the nature of the Oyster device means that this can be accomplished with a minimal decrease in power. This is discussed further in the following section.

4.2 (c) Maintainability and Reliability

Maintainability and reliability are crucial considerations for any marine device operating in a harsh environment. The need for WECs to be sited in high energy locations only serves to underline this point. All WECs, regardless of the level of reliability achieved, will require planned and unplanned maintenance during their lifetime. The challenge for designers is to minimise the impact of component failures on availability and power production at an acceptable cost. This requires early consideration of the planned maintenance strategy and the impact of, and ability to respond to, unplanned failures.

It must be stressed that Oyster avoids a significant maintenance challenge by siting the hydroelectric power take-off (including all major electrical equipment) onshore. Equipment can be accessed safely and easily around the clock, irrespective of weather conditions. However, the challenge of ensuring the reliability and availability of the offshore components of Oyster must still be met.

The wave climate at a typical WEC deployment site illustrates the difficulties faced in offshore maintenance. For all WECs, that are not accessible from land, any offshore intervention requires a calm weather window. Steps can be taken in the design to reduce the sensitivity to either weather window duration or the permissible operating conditions, but the extremely harsh offshore environment can make even relatively brief windows of acceptable significant wave height (H_s) scarce. Figure 11 shows the annual average number of weather windows for different window durations for a typical wave energy site in Scotland.

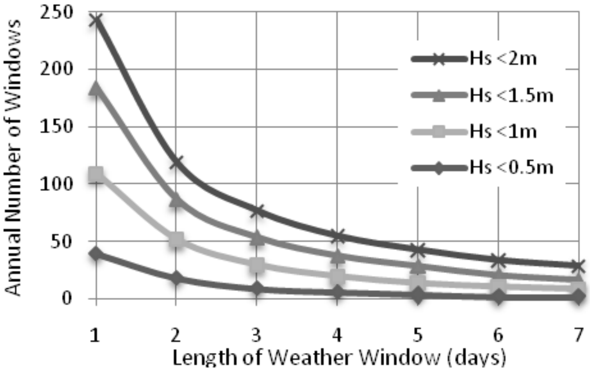

Figure 11: Average annual weather windows versus window duration for four different significant wave heights at a typical wave energy site in northern Scotland (Henry et al. 2010)

The weather requirements can significantly limit the number of opportunities for offshore intervention in a given year. Furthermore, the seasonal distribution of weather windows must also be considered. A failure during the more energetic winter months could have a much larger impact on availability than one during summer. Figure 12 shows the probability distribution, in winter and summer, of the time until a three day weather window with a significant wave height of less than one metre for a typical wave energy site in Scotland. Long wait times are not uncommon in winter.

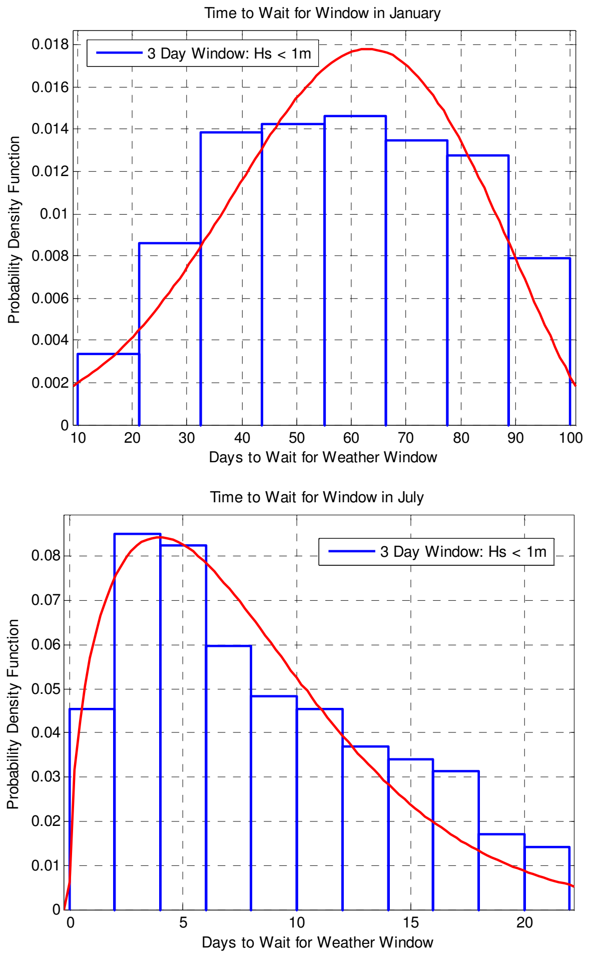

Figure 12: Probability distribution of the wait time for a three day weather window with a significant wave height of less than 1 m for a typical wave energy site in Scotland. Top plot shows winter (January) with a mean wait time of 58 days while the bottom shows summer (July) with a mean wait time of 8 days.

This wait time can also have a significant impact on the overall power generation of a WEC. The overall availability of a WEC can be estimated by considering the number of components, their individual mean times between failures (MTBFs), the impact on availability of any single failure, any redundancy inherent in the system, maintenance logistics, and the duration and nature of the sea states required for maintenance operations. In order to improve availability, each of these individual aspects should be considered during the design process.

Figure 13 presents the results from a stochastic component failure and maintenance model. During any discrete time step the model determines the probability of component failure or, following a failure, the probability of a suitable weather window becoming available for repair. It shows the negative impact on annual energy capture that unplanned maintenance can have for a hypothetical WEC due to the downtime that occurs while waiting for appropriate intervention conditions. Although this is a theoretical device, the sensitivity to duration and nature of weather window is clearly apparent.

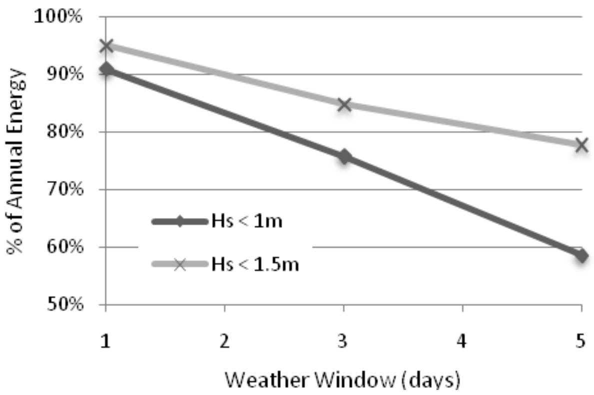

Figure 13: percentage of annual energy capture that is achieved due to unplanned maintenance requiring different window durations or sea states for a hypothetical WEC comprising 23 components with a MTBF of at least 25 months.

4.3 Design Decisions and Tradeoffs

The economic feasibility of a WEC clearly improves with an increase in the generating capacity of each unit. The cost benefits associated with a single larger unit compared to multiple smaller devices (one-off foundation/mooring costs, reduced vessel deployments, component cost savings and reductions in future maintenance interventions) generally outweigh the capital cost assocated with the increased scale of the device [8]. A significant increase in the scale of each Oyster unit was a fundamental consideration in the design of the next generation of the device.

A series of single parameter studies provided the starting point for this work. The suite of tests used Oyster 1 as a baseline and varied only one aspect of the device at a time. Four key design factors were investigated at this stage; flap thickness, width, freeboard and device depth. The results of these studies were used to create a parameter map assessing energy capture performance around the Oyster 1 reference point and, importantly, the corresponding extreme foundation loads were also recorded. A key observation was that wider flaps not only increase power captured but also increase capture efficiency.

The potential performance improvements that could be achieved by simultaneously modifying a number of the basic design parameters was investigated. An ideal flap design would maximise the energy capture while minimising the loads that exerted on the device structure and foundation. An understanding of the hydrodynamics of the flap was key. Testing of flaps with different characteristics shows that both pitch stiffness (the effect of the buoyancy of the flap as it attempts to right itself) and turbulent edge effects (vortices caused as the flap moves relative to the adjacent water particles) were major factors in driving device performance and extreme loads.

This led to the testing of a number of different flap end profiles, as shown in Figure 9. Adding rounded end effectors resulted in significant gains in wave energy capture efficiency whilst maintaining acceptable foundation loads. The Froude scaling employed during the model testing results in some uncertainty in scaling the results of the dog-bone shaped flap up to a full sized device; however the moderate cost of such a feature and the potential performance improvements justify its use in the Oyster 2 design.

Maximising power output from a single device was a key objective during the design of the next generation of Oyster. There are several factors that limited further increases in the flap width:

- Excessively wide flaps result in a decrease in capture efficiency due to phase variation of the wave force across the flap for non-orthogonal wave fronts [[1]] and the onset of the "terminator effect" [4].
- Wider flaps experience greater structural loads.
- Installation and maintenance considerations, and the structural span between hinge points, place limits on flap width.

A final suite of tests were carried out to investigate the 'dog-bone' flap's performance and loading characteristics for different pitch stiffnesses and widths. Figure 14 shows some of the results of this study. These data provided the basis for a series of design trade-offs between foundation feasibility, required flap structural strength, engineering cost and power capture efficiency.

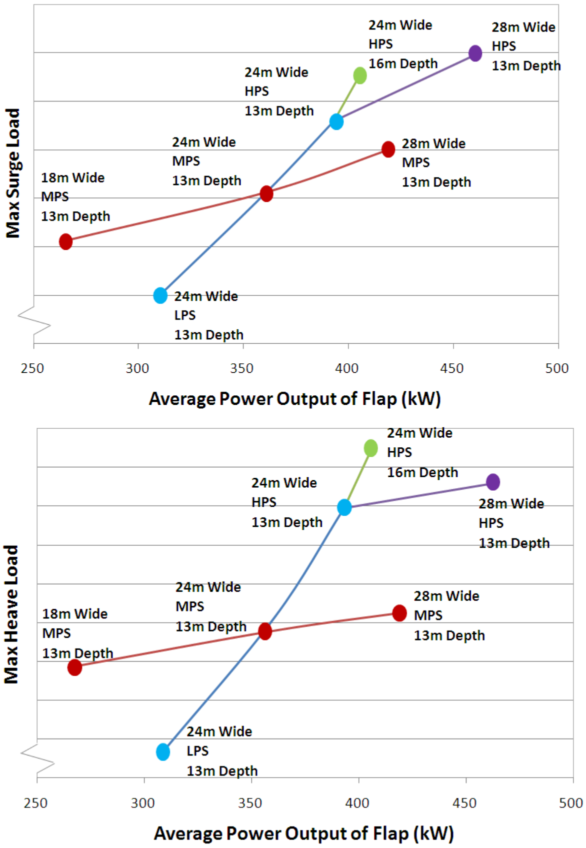

Figure 14: Maximum recorded surge (top) and heave (bottom) loads versus time averaged flap power output in a representative wave climate for different combinations of flap width, pitch stiffness and water depth. Low, medium and high pitch stiffness represented by LPS, MPS and HPS respectively

Structural constraints effectively limited the width of the flap and, combined with the measured performance data, drove a decision to adopt a 26 m wide oscillator for Oyster 2 with a relatively high inherent pitch stiffness.

All these tests and studies were conducted in order to determine the optimum characteristics of the oscillator/flap. In parallel, the overall layout of the offshore components was developed with regards to offshore installation and maintenance. It is vital that the hydraulic components on the offshore device can be accessed for maintenance. In the interest of safety, this maintenance will be performed with the flap locked or ballasted down on the seafloor. Serviceable components should be accessible with the flap in this position. Consideration of these factors drove the layout shown in Figure 15. The baseframe and hydraulics are offset to each side of the flap. This also led to a further safety feature where the flap can be locked down remotely in the event of a major failure.

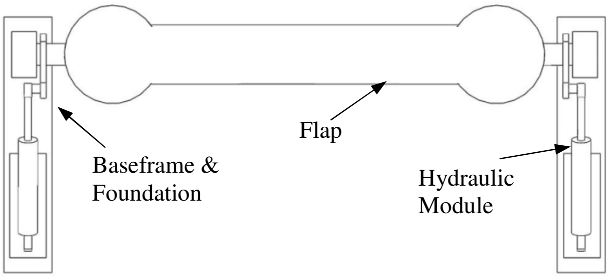

Figure 15: Illustrative outline of Oyster 2 in plan view

Figure 15 shows that the Oyster 2 device utilises two separate hydraulic modules; one at each end of the flap. Each module combines all the offshore components that could require maintenance into discrete removable units. A maintenance-by-replacement philosophy will be implemented by swapping a whole hydraulic module in a single offshore operation. A failed module, or one requiring routine servicing, is replaced by a pre-commissioned module and taken ashore for maintenance. This reduces the required weather window duration and avoids difficult and expensive offshore intervention and means that power generation can recommence within a short time frame.

A further advantage is the additional level of redundancy that is achieved with twin hydraulic module system. Each of the modules is a standalone unit that can continue to operate in the event of a failure in the other. The improved device availability due to duplication of the hydraulics outweigh the cost and maintenance of the additional offshore components.

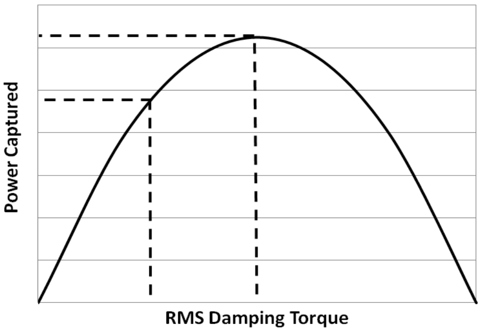

Figure 16: Typical Oyster power capture profile vs. applied root mean square (RMS) damping torque for typical sea state [4].

Even with one hydraulic module non-functional, performance is largely maintained due to the relative insensitivity of Oyster's power capture efficiency to the applied damping torque. Figure 16 illustrates the typical power capture profile versus applied damping torque (the resistance to flap rotation that is created by pressurising the hydraulics) for a typical performance sea state. In the event that the applied damping torque is halved, for example during the outage of an individual hydraulic module, the device only loses a small proportion of its power production. Oyster will continue to produce approximately 75 percent of the power that was generated prior to failure [4].

The required range of damping torques was also considered in the design of the hydraulic system. This determines the required range of system pressures. As mentioned in Section 2.3(b), the control system regulates damping torque over a relatively long time frame depending on the prevalent wave climate. The hydraulic rating of the offshore PTO (and thus cost) can be reduced significantly by reducing the allowable range of damping torques. Importantly, this has very little impact on power capture due to the natural response of the Oyster device; Figure 17 shows the difference in power output from a full achievable torque range down to a single universal damping torque. Even a 50 percent reduction in torque range gives less than a 2 percent reduction in power.

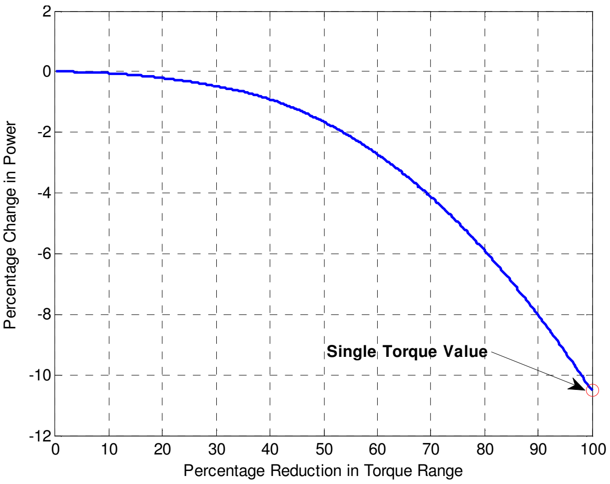

Figure 17: Effect of achievable torque range on power capture. The 'single torque value' highlighted is the global torque estimate, i.e a weighted average of the optimal damping in each sea state

A similar approach has been taken to improve availability of the onshore electrical equipment. Twin sets of electrical generation equipment are used. Each generator and the associated power electronics only need to be half the combined maximum rated capacity of the three offshore wave capture devices. Only one set of electrical generation equipment is used during lower energy sea states. Higher energy seas utilise both generators. This gives markedly higher overall efficiency as the power electronic fixed losses are reduced during periods of lower wave energy. The additional capability to maintain one drive train while operating on the other also offsets the expense of the additional hardware. Furthermore the electrical equipment uses water cooling in place of air cooling to avoid the potential corrosion affects of the coastal salt-laden air.

5. Conclusions

This paper provides an overview of the Oyster concept and an update on the successful deployment and commissioning of the first device at full scale in the North of Scotland. The paper also gives a summary of the design strategy for the next generation of Oyster device and presents some of the high level design features.

The following summary points are presented for consideration:

- The characteristics of the wave climate in the nearshore region provide a number of advantages for surging WECs; potentially harmful extreme storm events are filtered out and the directional spectrum is concentrated. The nearshore region has levels of exploitable wave energy that are closely comparable to those found in deeper water. Furthermore, the proximity to shore allows an onshore PTO with significant benefits for device maintenance.
- Oyster has been designed to maximise power capture by optimising the installation depth and flap width, using the full height of the water column, and a low hinge point. All factors increase the wave force which is the primary determinant of power capture for this type of device.
- Maintainability is a key driver for the lifetime cost of delivered energy. Considerable delays can occur in waiting for weather windows suitable for offshore intervention. This can have a large impact on the overall availability, and thus delivered power, of a project. Oyster 2 has been designed to have a modular maintenance-by-replacement philosophy for its offshore components and uses an onshore hydroelectric PTO for ease of access.
- Large gains have been made in the performance of Oyster 2 through research into the hydrodynamics of the oscillating flap. This has been balanced with structural and cost constraints to deliver a design which is rated at 2.5 times the power output of Oyster 1 but is only 50% wider.

This paper discusses just some of the key results and design features that have been considered in the development of the next generation of Oyster device. More detail will become apparent in future publications and with the deployment of the Oyster 2 project in 2011.

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Acknowledgements

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