ADVANCES IN THE DESIGN OF THE OYSTER WAVE ENERGY CONVERTER

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SUMMARY

This short paper, structured in 3 distinct sections will touch on some of the key features of the Oyster wave energy device and its recent development. The first section discusses the nature of the resource in the nearshore environment, some common misunderstandings in relation to it and its suitability for exploitation of commercial wave energy. In the second section a brief description of some of the fundamentals governing flap type devices is given. This serves to emphasise core differences between the Oyster device and other devices. Despite the simplicity of the design and the operation of the device itself, it is shown that Oyster occupies a theoretical space which is substantially outside most established theories and axioms in wave energy. The third section will give a short summary of the recent developments in the design of the Oyster 2 project and touch on how its enhanced features deal with some of the key commercial and technical challenges present in the sector

1. INTRODUCTION

Aquamarine Power Ltd was formed in 2005 to develop Oyster, a wave energy converter that interacts efficiently with the dominant surge forces encountered in the nearshore wave climate at depths of 10 to 15 metres. The Oyster concept consists of a large buoyant bottom-hinged oscillator that completely penetrates the water column from the ocean surface to the seabed. The surging action of waves on the oscillator drives hydraulic pistons, which pressurise freshwater causing it to be pumped to shore through high pressure pipelines. The onshore hydroelectric plant converts the hydraulic pressure into electrical power via a Pelton wheel, which turns an electrical generator. The low pressure return-water passes back to the device in a closed loop via a second pipeline.

Aquamarine has been almost exclusively focused on bringing the Oyster concept to full commercialisation since its inception. Following 2 years of extensive wave tank testing, computational modelling and innovative engineering design work, the first full-scale proof-of-concept device ('Oyster 1') was manufactured at the Isleburn shipyard in Nigg, in 2008. In a major milestone for Aquamarine, Oyster 1 was successfully installed at the European Marine Energy Centre (EMEC) in August 2009. Its successful commissioning in the high-energy open sea environment off Orkney, with first power to grid in October 2009, represents the delivery of a key technical milestone for the company and the entering of a new phase on the way to commercialisation.

The experience gained during this development and deployment process, along with the performance and condition data that has been gathered from the installed device, has dictated the nature of the next evolution of the Oyster concept that is currently under development. The 'Oyster 2' project involves the design, manufacture and deployment of three next-generation Oyster units at EMEC in summer 2011 with a total generation capacity in excess of 2MW. A successful demonstration project at this scale is required to prove the technology, reducing technical and operational risks associated with large-scale deployments to a level which is commercially attractive to mainstream investors.

The first generation of device had demonstrated that good energy capture factors could be achieved from bottom hinged surging wave power devices in the nearshore while exposing them to acceptable foundation loads. However ongoing work had shown that there was the opportunity for the next generation of device, Oyster 2, to make considerable improvements in its efficiency in the conversion of wave power to electrical power. A significant programme of R&D work was carried out in collaboration with Queen's University Belfast to determine what improvements in device geometry would deliver the greatest benefits, the results of which are touched upon here.

This paper begins with a discussion of the nature of the nearshore wave climate and the energy levels encountered there, it then describes the fundamentals of flap type surging wave energy converters before introducing the reader to the key design features of the Oyster 2 project that have resulted from Aquamarine's experience with the Oyster 1 project and the above body of R&D work.

2. NEARSHORE WAVE CLIMATE AND RESOURCE

There are three regions where wave energy converters (WECs) are sited and the location of the WEC often dictates its design. The first region is offshore and generally corresponds to deep waters, typically greater than 50m. Because of the water depths involved most offshore WECs are moored floating devices.

The second region is shoreline and, as the name suggests, WECs in this area are sited on the land and typically operate in a water depths of less than 10m. These shore based devices generally make use of the local topography to form the main body of the converter, such as LIMPET [1], and present designs often seek to be incorporated in to manmade structures such as breakwaters such as that in the town of Mutriku in the Basque country of northern Spain. [2]. The shoreline region has received significant attention due to the ease of access to the WEC; however loss mechanisms such as wave breaking (Figure 4) and seabed friction cause a significant reduction in the available resource.

The third category is the nearshore and while strict boundaries do not exist, this region is generally considered to have water depths between 10 and 25 metres. Due to the shallow or intermediate water depths in this region the few WECs that occupy it tend to be mounted on the seabed rather than moored.

2.1 THE EXPLOITABLE WAVE RESOURCE

The wave energy resource is commonly defined for a location by the average wave power, having units of kilowatts per metre. It has been accepted for sometime [3] that, in the context of wave energy conversion, this measure is an inadequate and perhaps misleading as it represents the omni-directional gross wave power passing through a point in the ocean. Moreover this gross wave power figure includes infrequent extreme sea conditions containing many times the wave power any WEC can hope to extract. Therefore in order to compare and select sites for WECs a more informed and refined resource measure should be used, namely the ‘exploitable wave power’.

2.1 (a) Directional Considerations

While an axi-symmetric point absorber may be capable of absorbing energy just as efficiently from a wave train approaching from various directions this is not the case for a wave farm of such devices. It would seem most effective to align the principal axis of the array towards the mean wave direction, weighted by the exploitable wave power, in order to maximise the power output from the array. Therefore, in order to determine the resource available to or incident on the array the wave climate must be specified as the net wave power, or that crossing a line orthogonal to the mean wave direction.

It is well known that the directional spectrum of wave energy is tightened as waves travel into shallow water due to refraction. Figure 1 shows the reduction in the directional spread of wave power from the offshore to nearshore at the EMEC site, Orkney.

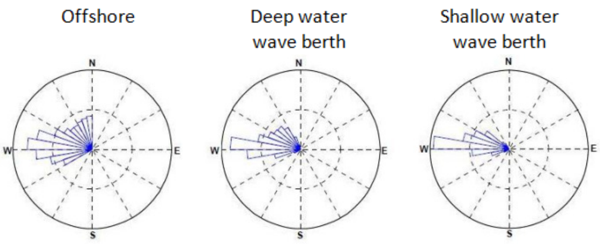

Figure 1: Wave roses for 3 locations at EMEC [4]

2.2 (b) Finite Device Capacity

The gross wave power resource figures include infrequent storm events which generate large swells containing wave power levels of 2 to 3MW/m, far greater than the average power levels, 50 to 75kW/m. These infrequent and short duration events may contain a significant proportion of the total resource but the power take off (PTO) system of a WEC will be sized in accordance with an appropriate load factor not in order to capture these extreme levels of power. Typically this load factor will be approximately 30 percent, much like that of a wind turbine, and therefore, assuming a reduction in hydrodynamic power conversion in larger sea states it can be argued [5] that the threshold for exploitable wave power should be in the region of four times the average wave power. This will be common to all WECs and therefore including these unexploitable portions of the wave climate in the assessment of the resource is misleading both for the device designer and for the site selector.

2.1 (c) Gross versus Exploitable Resource

Furthermore, Folley [5] models the wave climate to assess the resource at different locations at the EMEC test site. The results, presented in Fig 2, shows that the gross wave power offshore is twice that of the gross power in the nearshore, 10 metre depth; however comparing the deep water, 50 metre, and nearshore berths at EMEC reveals that there is only a 10 percent difference between the exploitable wave powers at the two sites.

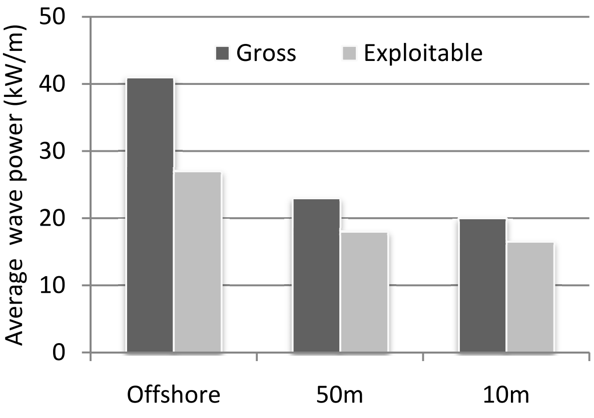

Figure 2: Average gross and exploitable wave power at three water depths at EMEC [5].

2.2 EXTREME WAVE CONDITIONS

While the structural design of any WEC may be largely influenced by loading during normal operating conditions, the device must also be designed to survive the infrequent extreme conditions that it will encounter over its lifetime. In the offshore region the extreme wave heights maybe 20 times that of the average operating wave height. This poses a significant design challenge and means that for most of its life much of the structure of the WEC is over-engineered and redundant leading to inefficiencies from a cost perspective.

However in the nearshore region these extreme wave conditions are affected greatly by the predominant loss mechanisms of wave breaking and seabed friction meaning that there is a natural filtering of extreme conditions in the nearshore.

Data from Aquamarine Power's Mike21SW [6] wave resource model is presented in Table 1. The data, which relates to four large storm events, illustrates the filtering of large waves as they travel into shallow water, where the maximum wave height at the 12 metre contour can be 8.7 metres while offshore it is 18.1 metres.

Table 1: Maximum wave heights (m) off the coast of Donegal, Ireland, during four major storms

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

2.3 RESOURCE SUMMARY

The nearshore region has largely been overlooked by the wave energy community as it appears on first inspection to offer neither a substantial resource nor ease of access. However, it has been shown that the exploitable wave power in the nearshore region is only marginally lower than that found offshore while the deleterious extreme events found in the offshore region are filtered in the nearshore and the directionality of the approaching wave fronts is improved. It is argued that the presently marginalised nearshore region should be more accurately characterised as a more consistent, directionally concentrated resource with limited extremes. When combined with the proximity to the coast that the nearshore water depths typically allow, with the resulting cost implications regarding power transmission and the possibility of onshore PTO provision, then this region can be seen to have significant advantages for the appropriately designed WEC.

3. FLAP TYPE DEVICE FUNDMENTALS

This section presents a brief description of the fundamentals of wave energy conversion followed by a pragmatic description of the hydrodynamics of pitching flap type wave energy converters. It will be shown that the power capture of this device type is linked strongly to the incident wave force and that high wave force and tuning appear to be mutually exclusive. Finally some results from experiments undertaken will be used to illustrate the salient points of the discussion.

3.1 CLASSICAL WEC THEORY

When a body oscillates in still water it creates waves at the frequency of oscillation. The amplitude of this radiated wave depends on the size of the body and the amplitude of its motion. Wave energy absorption can be understood as destructive interference of this radiated wave with an incident wave when the correct phase relationship is present. Wave energy is proportional to the square of the wave amplitude; similarly the reduction in the incident wave amplitude is related to the energy absorbed by the device. In a two-dimensional formulation of the problem a symmetrical body, oscillating in one degree of freedom, tuned to the wave period and damped appropriately, can theoretically only absorb 50 percent of the incident wave energy, as 25 percent is transmitted in the direction of the incident wave propagation and 25 percent is reflected. However, it must be understood that this formulation relates to two-dimensional theory which is only applicable to terminator type devices, that is, devices which are considered either large with respect to the wavelength or forming an infinite line parallel to the wave front.

When the problem of wave energy absorption is considered in three dimensions the result is a description of a point absorber [7, 8 & 9]. Point absorber theory suggests that if the body is assumed small with respect to the wavelength the power it may absorb is related, not to the size of the body, but to the wavelength. Therefore point absorber theory offers the WEC designer the opportunity to create a small WEC capable of absorbing large amounts of energy from outside of its physical bounds. Furthermore, the portion of the wavelength which may be absorbed by the body is determined by the mode in which it oscillates, which determines the shape of the wave pattern it radiates.

$$\mathrm{P}_{\max} = \varepsilon \frac{\lambda}{2\pi} P_i \qquad \text{Eqn. 1}$$

Where P_i is the incident wave power per unit crest length, ε is 1 for a heaving device and 2 for a surging device. It is important to point out that, from equation 1, a body oscillating in surge is theoretically capable of absorbing twice the power of that of a body oscillating in heave.

While point absorber theory is appealing in its simplicity its assumptions are worth considering. Firstly, it is based on linear theory and therefore it is assumes that the waves, forces and responses are all linear and non-linear forces such as viscous loss effects are neglected. Secondly, the velocity of the device must be kept in phase with the wave force. This represents a significant engineering challenge in real time-varying polychromatic sea states. Lastly, in order to absorb the large power levels predicted by the theory the oscillating body must often have amplitudes of motion significantly greater than the wave amplitude. It is clear that these large amplitudes of motion predicted are both unrealistic and undesirable. The effect of 'suboptimal' amplitudes of motion on power capture has been investigated by [10].

When a more realistic view of the hydrodynamics is taken it is clear than the high levels of power absorption predicted by point absorber theory are unobtainable. Furthermore the theory provides little design guidance for the designer of a WEC. The following section looks at the hydrodynamics of a flap type wave energy converter using a conceptual model based on empirical data and a pragmatic view of the hydrodynamics which can be used to inform the design process.

3.2 SURGE WAVE ENERGY CONVERTERS

Equation 1 implies that, theoretically, a WEC oscillating in surge can absorb twice that of a body oscillating in heave but yet there are surprisingly few WECs that move horizontally. Of course horizontal motions are difficult to provide due to alignment issues and the provision of end-stops to avoid catastrophic overrun in extreme sea conditions should preferably be avoided [11]. Therefore a simple method of absorbing wave surge energy is to use a hinge or bearing to allow the body to oscillate in pitch which then turns the surge force into a moment, or wave torque. Moreover, a purely surging device has no inherent spring force to aid in tuning and to resist nonlinear drift forces. However pitching devices do, whether it is excess buoyancy for a bottom hinged device such as Oyster or mass for a top hinged device such as Pendulor [12].

It will always be beneficial to tune a wave energy converter to the incident wave period. Heaving buoys tend to be spring dominated, having very low natural periods and therefore methods such as latching control [13] have been proposed to lengthen the natural period of oscillation to match that of the incident wave period. The dynamics of bottom hinged pitching flap type WECs tend to be inertia dominated and therefore the natural pitching period is generally well above that of the most common wave energy periods, say 5 to 15 seconds. The natural period, T_N, maybe calculated using Equation 2.

$$T_N = 2\pi\sqrt{I + k_P} \qquad \text{Eqn. 2}$$

Where I is the total moment of inertia and k_p is the pitch stiffness. The pitch stiffness is a restoring moment due to the buoyancy of the flap. The inertial term is made up of the moment of inertia of the mass of the flap and the added moment of inertia associated with the mass of the water forced to move with the flap. The inertial term is generally dominated by the added moment of inertia, which is typically ten times the moment of inertia of the flap's mass.

In order to tune a pitching flap it must be of small width and draft so as to reduce the added moment of inertia, while having significant thickness so as to provide sufficient displaced volume to maximise the spring term. In practise this leads to a flap, of relative density 0.5, having dimensions in the order of a 6 metre cube.

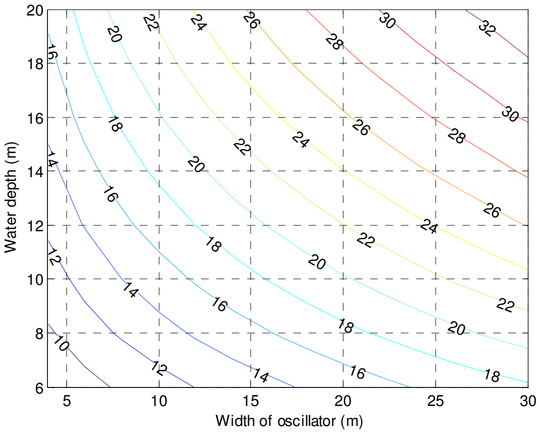

Figure 3: Variation of natural pitching period (sec) with flap width and water depth [14]

This small flap may have a natural pitching period of approximately 10 seconds but it is shown in [15] that due to the motion constraints, and viscous losses, the power absorption levels predicted by point absorber theory are still unachievable. In fact it is argued that if a pragmatic view of the hydrodynamics of a pitching flap type device is adopted then it is the wave force that dominates the performance of the device.

3.3 WAVE FORCE

For a body which is considered small with the respect to the wavelength the long wave approximation of wave force [16] can be used to show that the surge wave force is approximately proportional to the added mass, as shown in Equation 3

$$F \approx (M_d + M_a)\xi\omega^2 \qquad \text{Eqn. 3}$$

Where F is the wave force, M_d is mass of the water displaced by the body. M_a is the added mass, ζ is the horizontal water particle amplitude and ω is the wave frequency.

As discussed earlier, in order to tune the device the added mass must be reduced but to increase the wave force the added mass must be increased. This means that resonance and high wave force appear to be mutually exclusive for a pitching flap.

It is also interesting to note from Equation 3 that the wave force is proportional to the square of the wave frequency and therefore, for a constant added mass and wave height, the wave force is higher in the shorter more commonly occurring sea states and reduces in the longer wave periods associated with damaging storm events.

3.4 MAXIMISING WAVE FORCE

There are four main geometric flap characteristics that must be considered to maximise the wave force on the pitching flap.

Firstly, to maximise wave force the water column should be blocked. Leakage under, over or through the flap will mean a reduction in wave force and thus a loss of performance. Experiments undertaken at Queen's University Belfast [17] have shown that leakage under or through the flap can result in a power loss of up to 30 percent. Wave overtopping losses can be higher still and freeboard, the height of oscillator protruding above the ocean surface, must be chosen carefully to maximise power output in operating sea states.

Secondly, as the flap is constrained to move in pitch rather than in surge the wave force acting on the flap becomes a moment, or wave torque. Therefore, 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.

The third parameter used to maximise wave torque is the water depth in which the device is located. It is shown in [15] that the amplification of horizontal water particle motion, due to shoaling in shallow water, will increase the surge wave force by approximately 1.5 times that experienced by the same body in deep water. Therefore the performance of a flap type WEC can be increased by moving it into shallower water, even when considering the energy losses as waves travel into the nearshore region. However, it is clear from Figure 4 that water depths less than 10 metres are to be avoided because of the sharp drop off in wave energy due to wave breaking. Furthermore the dynamics of a flap in very shallow waters changes significantly over a tidal cycle when a typical tidal range of 3 metres is considered.

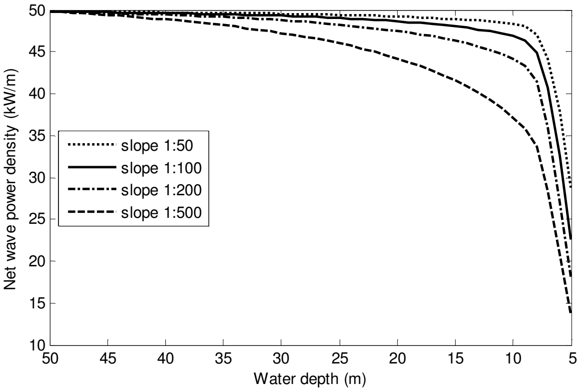

Figure 4: Reduction in net wave power with water depth over various bed slopes [4]

With the optimal water depth established, flap width is the final remaining design variable that can increase the wave force and thus power capture. With wave force linked to the added mass it can be shown that wave force increases with the square of flap width. However this increase is only valid within the bounds of the long wave approximation. Figure 5 shows the phase angle between the wave force and the wave crest for flaps of various widths obtained using WAMIT®.

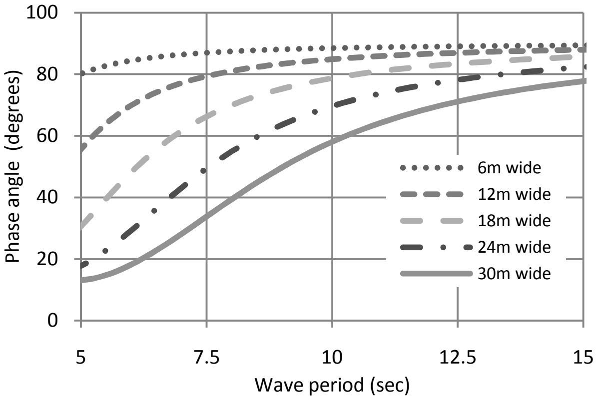

Figure 5: Wave force phase against wave period for various flap widths modelled using WAMIT®.

Figure 5 shows that for flaps with a small width the wave force has a phase angle of 90 degrees to the wave crest meaning the force is in phase with the horizontal water particle acceleration, thus satisfying the long wave approximation. However, as the flap width increases, the force tends towards zero phase angle, especially at shorter wave periods, and the long wave approximation becomes less valid. At this point the hydrodynamics are tending towards a two-dimensional scenario where the flap may be described as a terminator and its power capture will be limited to a maximum of 50% of the incident wave energy as discussed earlier

Therefore care must be taken in selecting a flap width which will maximise the wave force in the most commonly occurring sea states, without making it too wide so that performance is compromised in the shorter period sea states.

3.5 SUPPORTING TANK TEST RESULTS

Wave tank experiments were undertaken at Queen's University Belfast [17] using four different width 20th scale models in several random sea states representative of the northeast Atlantic wave climate. The results were weighted by each sea state's frequency of occurrence to determine average power capture.

It should be noted that for each of the configurations tested the flap construction was the same, such that the pitch stiffness increased linearly with width whereas the added mass increased approximately with the square of the width. Therefore the natural pitching period increases with width (14.3, 17.9, 20.0 and 23.0 seconds for the 6, 12, 18 and 24 metre wide flaps respectively) making the wider flaps more detuned.

The average annual power capture for each flap width is plotted in Figure 6. It is perhaps not surprising that power capture increases with flap width. However it should be noted that the 18 metre wide flap captures approximately six times as much power as the 6 metre wide flap, while it is only three times as wide. It should be noted that the results do not correspond directly with the performance of either the Oyster 1 or Oyster 2 flaps, which include other features and performance enhancements, but relate to generic test cases.

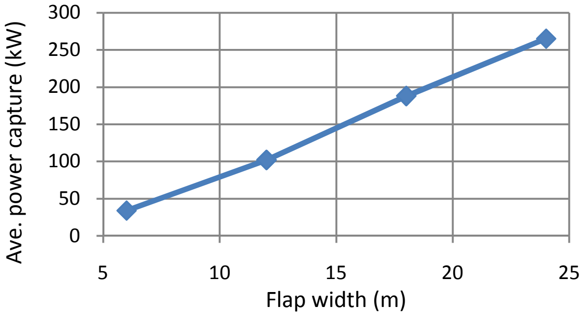

Figure 6: Average power capture against flap width

A commonly used measurement of wave energy absorption efficiency is capture factor. Capture factor is the ratio of power captured by the device to that incident across its width. The results of the experiments are used to calculate an average annual capture factor for each flap width and are presented in Figure 7.

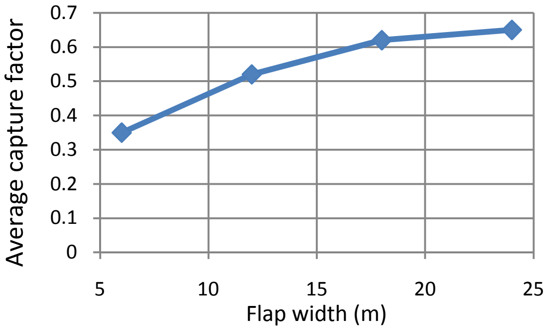

Figure 7: Average capture factor against flap width

The data shows that there is increased efficiency with wider flaps. For example the 18 metre wide flap is twice as efficient as the 6 metre wide flap. The shape of the curve in Figure 7 also hints at a possible limit in improving average capture factor simply by increasing flap width.

3.6 DEVICE FUNDAMENTALS SUMMARY

This section has provided an, albeit brief, description of the hydrodynamics of a flap type wave energy converter. It has been shown that a more pragmatic description of the hydrodynamics is required to inform the design process than that which prevails in standard point absorber or terminator theory.

It is found that the performance of this device type is dominated by the wave force it experiences and guidance on how to maximise this by altering the geometry of the flap has been provided.

4. OYSTER 2 CONCEPT DESIGN

This section of the paper outlines the main design features of the Oyster 2 concept and how these features are tailored to meet the technical and commercial challenges involved with commercialising wave energy devices. The ultimate design objective for commercial renewable energy devices is to deliver a competitive cost of energy over the operational life of a project. In determining the lifetime cost of energy it can be seen that device performance, device availability and capital costs are the three main drivers which designers must focus on. The following sub-sections detail the ways in which the Oyster 2 concept has been designed to deal with these three cost drivers.

4.1 OVERALL CONCEPT

The first aspects of the Oyster 2 design to emphasise are those fundamental features which have been employed in the earlier Oyster 1 design and which are retained for the Oyster 2 device. At the highest level the Oyster 2 devices are conceptually the same to the Oyster 1 prototype. The principle of the bottom hinged oscillator in 10 to 15 metres water depth continues to be exploited by the Oyster 2 design. The key characteristic of having hydraulic power transmission to shore and an onshore hydroelectric plant is also retained. The simplicity of the off-shore components from a reliability and maintenance point of view is one of the core features of the Oyster design. See simple illustration in Figure 8 below.

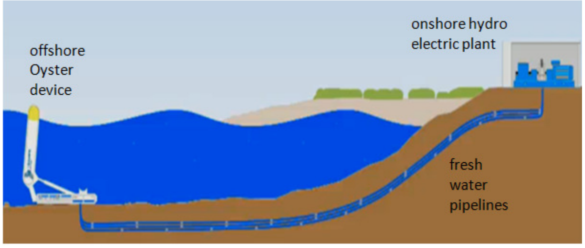

Figure 8: General outline of the offshore and onshore components of the Oyster concept.

4.2 FLAP AND SUB-FRAME CONFIGURATION

Some of the critical lessons learnt from the Oyster 1 prototype deployment related to the practicalities surrounding installation, access and maintainability. One of the primary design features of the Oyster 2 device is that it has its sub-frame, foundations and hydraulic power take-off located to the side of the main flap. See Figure 9 below for basic illustrative diagram of the device in plan view with the flap in a vertical position. This allows access to the foundation, main bearings and hydraulics with the flap in the closed/horizontal position and is seen as a key advantage for quick and efficient installation and maintenance operations.

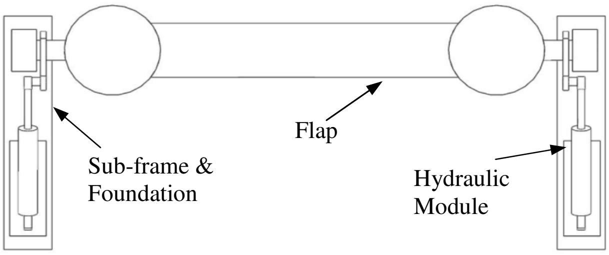

Figure 9: Illustrative outline of Oyster 2 in plan view

4.3 FLAP SHAPE AND STUCTURE

The Oyster 2 flap itself is 26 metres wide. The choice of the scale of the flap was made in light of various factors. The need for scale is apparent in a general sense because of the relatively small capacity of marine energy devices with respect to the rest of the power sector. As touched on in Section 3, wider flaps can lead not only to increased power captured, but also increased capture efficiency. There a several factors that limit the extent to which it is desirable to further increase the flap width. A decrease in capture efficiency with excessively wide flaps is experienced due to incoherence of wave force across the flap in off angle seas and the on-set of the "terminator effect" as discussed in Section 3. As flap width increases so do the structural loads that must be accommodated and there are obviously limits on the magnitude of loads that can be cost effectively handled with a given foundation solution. The decision to keep the flap hinge points and the sub-frame to the sides of the flap itself also means that, although maintenance access is improved the flap structure has to effectively span the distance between the sub-frames. As a result, structural constraints effectively limit the width of the flap and, combined with the measured performance data, drove a decision to adopt a 26 metre wide oscillator for Oyster 2.

As indicated from the illustration in Figure 9 the Oyster 2 flap in plan view has a distinctive 'dog-bone' shape. Bottom hinged flaps oscillating in a surging sea experience energy loss through viscous effects as a result of the relative velocity between flap and fluid. Tank tests were undertaken to examine if these losses could be reduced through modification of the edge profiles of the flap. From the variations tested it was found that the flaps with wide rounded ends (or 'end effectors') preformed best in terms of power capture. Scaling the observed performance improvements from model-scale to full-scale is not straightforward; however the relative capital cost of the end effectors as compared to the expected performance gains clearly favoured in the inclusion of the end effectors in the Oyster 2 design.

Other fundamental variables of the flap itself such as the pitch stiffness, relating to the buoyancy of the flap as it attempts to right itself, and its free board, the height of the oscillator protruding above the water surface, were optimised for energy capture and foundation loads as part of a significant concurrent program of tank testing. The pitch stiffness of the flap was increased over that of the Oyster 1 device. Similarly the free board of the flap was also increased at mean water level.

These improvements in the flap geometry and pitching characteristics mean that, although Oyster 2 is less than 50 percent larger than its predecessor in a physical sense, it will produce approximately 2.5 times the maximum power output.

4.4 AVAILABILITY AND RELIABILITY

While Oyster avoids a significant part of the maintenance challenge by siting many of its most complex components on-shore, the challenge of ensuring the reliability and availability of the offshore components remains. The Oyster 2 design addresses this issue in two ways. Firstly by minimising the duration, number and weather sensitivity of offshore maintenance operations, and secondly by building redundancy into the offshore hydraulic power take off system.

4.4 (a) Minimising offshore operations

As can be seen in Figure 9 the Oyster 2 device utilises two separate hydraulic modules; one on each side of the flap. Each module aggregates all the off-shore components which may require maintenance, within the device's operational life, into discrete removable units. Thus, by swapping entire hydraulic modules in a single offshore operation, a maintenance-by-replacement philosophy is adopted which precludes the need for difficult and expensive offshore intervention; a module requiring servicing is taken ashore for maintenance while a pre-commissioned module takes its place.

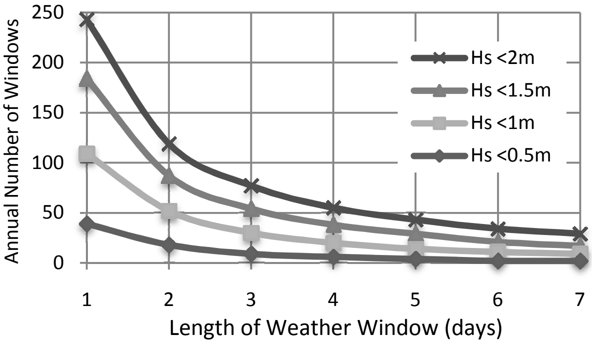

Figure 10: Average annual weather windows for a typical wave energy site in the north of Scotland

Critically this approach reduces the sensitivity of the maintenance operations to the duration and nature of the weather windows required to carry out the necessary offshore activities. This is an important factor given the potential downtime that could be experienced while waiting for a weather window in highly energetic locations. Figure 10 shows the average number of weather windows that could be expected each year for different window durations and below certain significant wave heights (Hs) for a typical wave energy site in Scotland.

Moreover, Figure 10 does not show the seasonal skewing that occurs with the majority of calm periods occurring in the summer months; making device intervention in the rest of the year even more challenging. With marine operations typically limited to significant wave heights of less than 1.5 metres the benefits of minimising offshore operations are self apparent.

4.4 (b) Redundancy

The hydraulic modules discussed in 4.4(a) are stand alone units each of which will continue to operate in the event of a failure in the other. This results in more offshore components as each cylinder must have its own set of accompanying valves and auxiliary hydraulics; however the additional redundancy provided by module duplication more than outweighs the impact of the increased offshore components on the net availability of the device. Figure 11 below 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 each sea state the system aims to operate at the optimal damping torque to maximise power output. It can be seen that in the event that the applied damping torque is halved i.e. during the outage of an individual hydraulic module, the device would not lose half of its power production. The reduction in applied damping torque causes an increase in the range of motion of the flap over a wave cycle which makes up for some of the loss in power. During the outage of a single hydraulic module the device will continue producing at approximately 75 percent of its pre-failure output.

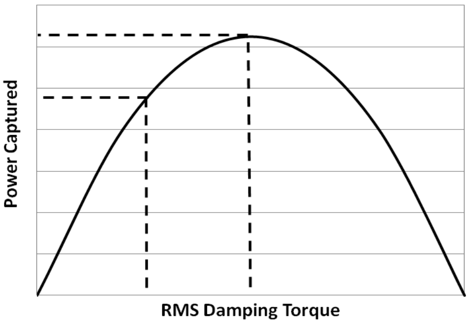

Figure 11: Typical power capture profile vs. applied root mean square (RMS) damping torque for typical sea state.

4.5 OYSTER 2 SUMMARY

Although retaining the fundamental concept of operation from Oyster 1, the Oyster 2 project is a significant improvement in both project scale and design. Not only will the installed capacity increase, but the design of each device will mark a step change in wave power conversion efficiency, maintenance philosophy and production costs based on lessons learnt from the Oyster 1 development process and test work conducted at Queen’s University Belfast. Design and testing to date have identified a design that, based on bottom up cost estimates, will deliver the necessary reduction in lifecycle cost of power to place Oyster within close reach of a commercial launch.

This section has presented some of the high level design features of the Oyster 2 project that will be deployed in 2011; however commercial sensitivities demand that other innovative aspects of the design must be the topic of future publications.

5. CONCLUSIONS

This paper has presented a case for the use of hinged oscillating WECs in the nearshore and the high level design features of the next generation of such a device that is being developed by Aquamarine Power, Oyster 2. In particular the following points can be concluded:

- The exploitable wave power (that portion of the energy that is actually useful for conversion by a WEC) in the nearshore region is only marginally lower than that found offshore. This small decrease in exploitable power is more than compensated by the fact that the harmful extreme events found in the offshore region are filtered in the nearshore.
- By utilising a pitching flap the extractable power is determined to be related to the wave force which in turn is approximately proportional to the horizontal water particle acceleration and the added moment of inertia of the water that is moved with the flap. It is shown that, even as the flap is not tuned to the incident wave period, it captures a large amount of power in the most commonly occurring sea states.
- Wave force (and thus captured power) can be maximised by obstructing the full water column with the flap, moving the hinge point close to the seabed, moving the device into shallower water while taking note of wave breaking losses and optimising the device width to gain the best possible capture factor.
- Large gains have been made in the performance of the Oyster 2 device through consideration of the above points in the design of the flap. Furthermore, design features that minimise the duration and number of offshore operations (as well as provide redundancy) address the critical issue of cost effectively maintaining WECs.

Due to commercial considerations, this paper has touched on just some of the key results and design features that have been considered in the development of the next generation of Oyster device. However even this is sufficient to illustrate the enormous promise in the Oyster technology as a nearshore surging device. More detail will become apparent in the future with further publications and the deployment of the Oyster 2 project in 2011.

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