

The Construction of Oyster – A Nearshore Surging Wave Energy Converter

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Abstract

In 2005 Aquamarine Power Ltd. was formed to develop Oyster®, a near shore flap which is hinge connected to the sea bed. With a combination of private equity and grant aid a 315kW Oyster module has been designed and manufactured. It is planned to install a prototype module at the EMEC test site in Orkney once the nearshore test berth is complete. Presently the power train is being tested and the instrumentation system calibrated. In this version of Oyster®, high pressure sea water will be pumped ashore to drive a Pelton wheel. Ultimately it is envisaged that Oyster units will be arranged in clusters feeding single onshore power take off units; which will form power stations of utility scale.

An extensive research and development programme has produced a very efficient structural form, which gives Oyster one of the highest power to weight ratios of all current technologies. This is combined with high capture factors in the most commonly occurring seas. The sea bed foundations and installation technique will enable Oyster to be easily removed and reinstalled for major maintenance when required. This is a feature normally associated with moored devices.

Although there are other bottom-hinged flap devices, Oyster is different in several ways and occupies a different part of the design space. For example, unlike the other systems it completely penetrates the water column from the water surface to the sea bed. Although it might be considered that such a system would be vulnerable in extreme seas, extensive wave tank modelling has shown that the flap intrinsically decouples from the wave as the oscillation increases and that the wave loads experienced are manageable in the three operational modes; generating, undamped and parked on the sea bed. However, model tests confirmed that Oyster can remain generating in all sea-states including plunging breakers.

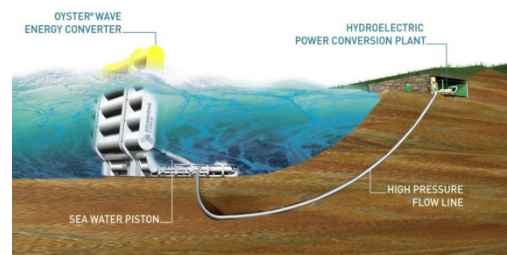
This paper charts the construction of Oyster presenting some of the challenges which have led to the current design. An outline of the impending

testing and sea trials of a prototype demonstration unit is given along with the projected outcomes.

Keywords: Oyster, shallow water, flap, surging, concept, loads, design, construction, array, performance, wave energy device

Introduction

The concept for a simple Wave Energy Converter (WEC) based on a bottom hinged flap was researched at Queens University between 2000 and 2005. Aquamarine Power was incorporated to commercialise the Oyster concept in 2005. In 2006, it was decided to construct, test and grid connect a full scale prototype of the concept. Between 2006 and 2008 a detail design of the concept named Oyster was developed leading to the fabrication of the WEC and the onshore Hydro-electric plant.



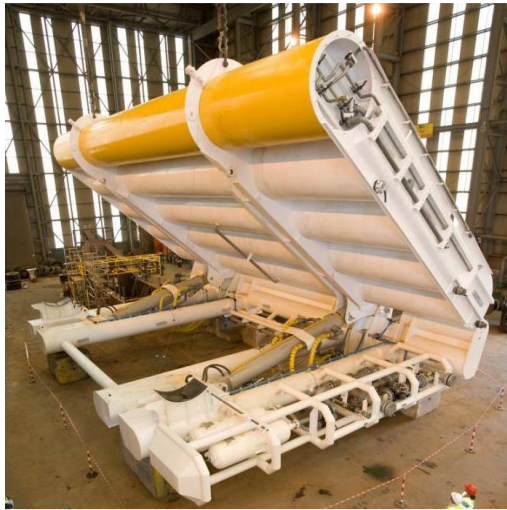
Oyster Concept Description

The Oyster WEC comprises an Oscillator flap mounted on a Sub-frame Support Structure. The oscillating action of waves on the flap drives hydraulic pistons, which pressurise seawater. The pressurised seawater is pumped to shore through the high pressure pipelines. At shore the hydro-electric plant converts the hydraulic pressure into electrical power via a pelton wheel, which turns the electrical generator.

Current Status

The fabrication of Oyster 1 is now complete and it will be installed at EMEC in the summer of 2009

after a series of full scale tests carried out over winter.



Oyster 1 WEC Complete at Nigg

Background

The use of an oscillating flap type wave energy converter is not a new concept and many patents have been filed regarding this method of extracting energy from sea waves. One of the most successful devices of this type is Pendulor, [2], which was built and tested in Japan. The Pendulor device consists of a flap or plate suspended from a horizontal shaft which spans a caisson. The flap is positioned at the nodal point, one quarter wavelength from the back wall, to exploit the local increase in particle motion due to reflection of the incident waves. In 2004, Queens University Wave Research Group recognized that the costs associated with the construction and installation of the caisson and back wall associated with the top hinged device may limit its commercial viability. They investigated a bottom hinged flap with no back wall and found that it demonstrated a number of excellent characteristics. Not only was it efficient at collecting wave energy from the most commonly occurring seas, but also its rotation allows overtopping; which naturally provided enhanced survivability in extreme seas without an active control system. These characteristics stimulated a research programme of both numerical and physical testing to understand how the performance of the device is influenced by flap configuration, damping and water depth. The results of the testing were promising enough for a group of investors to decide to develop the concept commercially. To execute this, a new company called Aquamarine Power Ltd was born and the device was named Oyster.

Oyster Development

The development of the Oyster design and construction was then carried out in a partnership

arrangement between QUB and Aquamarine Power.

The first decision to make was at which scale to prove the concept. All of the testing carried out by Queens had been undertaken at 1:40 and 1:20 scale. The options were; to move up through the scales cautiously or move directly to a full scale prototype.

There are advantages and disadvantages of each approach. The former approach of moving through the scales provides a set of new information regarding performance and construction techniques at each scale at a reduced cost. A gradual approach also takes a long time if each scale is investigated and tested before moving on to the next scale. Moving immediately to full scale demonstrates all the issues in the shortest time, but is higher risk as the full prototype cost is required without the ability to modify the design along the way. Most developers of wave energy converters have selected the former approach; however as the installation was considered to be one of the critical operations, the decision was taken by the Aquamarine Board to go straight to full scale. This decision has proved to be beneficial to the development process as discussed in this paper.

Oyster Design Overview

The Oyster prototype has been designed to capture wave energy and convert it into grid quality electrical power. This process involves essentially four conversion systems, each with its own piece of equipment that requires design optimisation. The four conversion systems are:

1. Hydrodynamic to Mechanical (WEC Flap)
2. Mechanical to Hydraulic (Pistons)
3. Hydraulic to Mechanical (Pelton Wheel)
4. Mechanical to Electrical (Generator)

The design development of each one of these conversion systems is described below.

Hydrodynamic to Mechanical Conversion

The design of the Oyster wave energy convertor had to balance capital cost with wave power conversion efficiency. The key wave power conversion parameters are water depth, flap geometry, buoyancy and damping. The key capital cost parameters for a flap type converter are similar with the addition of foundation loading. In simple terms, the design problem was to maximise the wave power captured per tonne of device and foundations.

The way Oyster extracts power from the waves is by modifying the horizontal (surge component) acceleration of the water particle motions which generate forces on the flap. The forces are

maximised by making the flap penetrate the full water column and minimising leakage underneath or from overtopping the device. Widening the flap also increases the forces approximately in proportion to the square of the flap width. However, as the width increases the maximum wave force reaches a limit due to phase incoherence across the flap. [1] Finally, as the water depth reduces the horizontal amplitude of the water particle motion increases but the overall power reduces.

However, optimising the power take off is not the end of the design story, there are also other considerations that if not properly taken into account in the design can significantly affect the installation and operation costs, namely:

- The location of the offshore site and seabed conditions.
- The method of fixing the structure to the seabed.
- The method of installation and removal of the WEC.
- The method of converting the wave energy, where the components of the power take of system are located and how they are to be maintained.

The requirement for the Oyster is to operate in the energetic near-shore environment of the Atlantic margins. A number of potential offshore locations were assessed, with the European Marine Energy Centre (EMEC) in Stromness, Orkney Islands finally selected. It is worth pointing out that although EMEC has been set up specifically to test wave and tidal devices, testing a nearshore device was not part of the original planning. Hence there are four offshore berths with cables to shore set up, but there was originally no nearshore berth or infrastructure. APL has now signed a contract for a new nearshore berth and is working with EMEC to create it. The nearshore seabed at EMEC is also challenging, it consists of faulted and fractured hard sandstone with steps and gullies up to 3 m high.

Various foundations systems were considered, including; gravity base, pad foundations with rock anchors and bored piles.

In principal, a gravity base solution provides the simplest option, however given the uneven nature of the seabed and high surge and heave loads; the size of the base was found to be impracticable. Therefore only the rock anchor and pile options were pursued.

The rock anchor foundation option assessed was based on four concrete pads, each tensioned down onto the seabed. The technical challenge was to design a solution that could accurately level the seabed with sufficient rock anchors to resist the wave loading, and could be installed by divers.

Installing rock anchors will require drilling of a series of holes. Albeit relatively small, these would be too large for hand held diver operated equipment. Therefore, a small drilling rig capable of drilling under water operated by divers was developed. A technical solution was found but it was calculated that a reasonable amount of dive time would be required to construct it. Given the limited weather window for diving operations on the site in Orkney, it was decided to adopt a more traditional solution for the prototype Oyster installation.

Piles are commonly used offshore for founding jacket structures. Generally at the jacket locations the seabed is normally covered in a thick layer of sand or clay sediments, which allow the piles to be driven. However, due to the rock at EMEC test site, a hole would have to be drilled first to form a socket in which the pile is lowered and grouted. This requirement requires a small drilling rig on a jack-up vessel, with a crane able to handle the size and weight of the piles. The design of the piles was further complicated by the fact that they had to resist uplift from the buoyancy of the flap as well as the wave surge forces; this factor determined the depth of the piles.

However, it was the requirement to install and remove the WEC from the foundations that generated one of the most difficult design problems to overcome. The original design assumption was that the WEC would be mechanically connected to the top of the piles, such that removal of the WEC for maintenance or decommissioning could be effected by either removing a pin or unbolting. The standard offshore solution for connecting superstructures to piles is either grouting of the collar between the pile and the structure, or swaging the pile onto the structure. Neither solution provides the functionality required. Many mechanical options were assessed but most required a level of construction tolerance not realistically achievable or they could not tolerate the uplift forces. The final solution selected was a simple bolted flange. The tolerance was overcome by introducing an intermediate pile connection frame which is match fitted to the WEC and grouted to the top of the piles.

A key objective in the development of the Oyster prototype was to be able to install and retrieve the WEC in littoral waters from a prepared foundation without the need to deploy expensive jack-up or heavy lift barges or vessels. This is essential for keeping down operating costs and increasing availability as specialist vessels are expensive to charter and not always readily available. Therefore an installation process was developed that took advantage of the buoyancy of the Oscillator flap and its ability to float and support the hydraulic cylinders and sub-frame during the installation

process. It should be noted that this strategy may not apply to the future installation of Oyster units in an array as it may be economic to develop a specialist vessel to service farms of Oyster units deployed around the UK.

However, the self installing strategy was found to be very difficult to achieve in practice. In hindsight, it was obvious; the WEC device was specifically designed to actively respond to wave motion and it was being installed in a highly active wave environment and unsurprisingly it was found that it also actively responded during installation. A number of different self installing strategies were investigated numerically and physically in the tank. Unfortunately, even in seas not significantly greater than flat calm the device responded with motions which would require a significant energy absorption system. The conclusion of the assessment was that the most cost effective installation option would be to utilise the jack-up that has installed the piles to also assist in the installation of the WEC. Working with offshore installation contractors, a solution has been found to achieve this.

Finally the design of the WEC must take into account the layout and support arrangement of the system used to convert from mechanical to hydraulic power. Wave Energy Convertors are characterised by systems with large torques but relatively small movements. The consequence is that the forces generated are large and change sign twice every wave period. This generates significant fatigue loading and for a steel structure, many parts of the structure fatigue will be the critical design criteria.

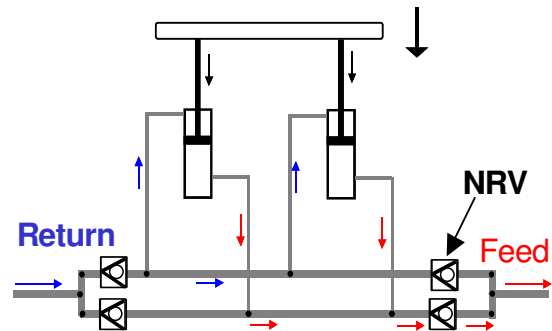
Mechanical to Hydraulic Conversion

Initial design effort focused on high pressure oil hydraulic power conversion system that consisted of four submersible induction generators directly coupled to and driven by hydraulic motors, valves, actuators, switchgear and controls mounted in an airtight subsea enclosure. However, after detailed design proved the concept viable, it was found that there were residual issues regarding reliability, maintainability, oil inventory, fault tolerance and cost that indicated a better solution lay elsewhere.

This led to the alternative strategy of delivering pressurised sea water to an above the water generator, placed either on the shoreline or on an offshore support structure. This solution had the added advantage that all the electrical generator, controls and switchgear could also be located above the waterline. This solution was adopted; for the Oyster prototype it is planned to have all the electrical equipment onshore.

All the mechanical to hydraulic conversion takes place on the wave capture unit, in an aggressive marine environment offshore, with little

opportunity for routine maintenance let alone fault correction. Therefore, at the early stages of the design a decision was taken to design a system on the WEC that had no active control systems and was fault tolerant. The basis of the design was the flap connected to a hydraulic cylinder and a series of check valves.



Pumping action as oscillator moves towards cylinders

The pistons are connected to the flap such that as it rotates the pistons are moved in the cylinders pressurizing the water. The check valves ensure that the flow is in the same direction for either direction of rotation of the flap. The damping torque, critical to the power capture, is determined by the area of the cylinders, the mounting eccentricity and the fluid operating pressure, so this had to be factored into the overall system design. They also determined the cylinder force which has a big influence on the structural design, especially fatigue design. Therefore, clearly getting the configuration of the cylinders correct has a significant impact on the overall performance and cost of the WEC.



WEC Check Valves and Manifolds

The main design decisions for the cylinders were type, material, number, and the method of mounting. Of course these all fed into the cost. A number of cylinder types were investigated including single acting, double acting, regenerative, displacement, fixed and rotating. Each type has advantages and the final decision was to select a pair of double acting cylinders constructed from mild steel coated internally. This balanced cost and durability.

The hydraulic system on the prototype is designed for three modes of operation. Initially the system will consist of only the wave capture unit

offshore, the pistons will pressurize a closed hydraulic system using fresh water as the hydraulic fluid, the wave power being extracted by the WEC will be calculated by the hydraulic fluid passing through an orifice plate.

Following these initial tests the system will be modified to include feed/return pipe lines to shore. This system will initially use fresh water in a closed system and as such will not be subjected to any significant particulate contamination.

The final stage will be to use an open system with filtered seawater drawn into the system from the area surrounding the WCU. This system will be subjected to particulate contamination.

The three stages are summarised below:

- Stage 1 – Closed loop freshwater system with no return to shore.
- Stage 2 – Closed loop fresh water and sea water system with return to shore.
- Stage 3 – Open loop sea water system with inlet filter located subsea.

All the equipment supplied for the Oyster prototype has been designed to operate for all three stages of the system testing.

Hydraulic to Mechanical Conversion

The challenge here was to design a mechanical and control system that could accept the water that was being pumped ashore at variable flow rates and pressures, and efficiently convert it to mechanical power. The choice was to use a marinised pelton wheel turbine directly coupled to a flywheel and a variable speed induction generator. The challenge is that a pelton wheel operates most efficiently when running at a constant speed; this requires a steady flow of water at a constant pressure. Whereas the Oyster WEC produces water that typically changes from no flow to peak flow and back twice every wave period (7-12 seconds). The solution developed was in three parts; the first part was to maintain and control the system pressure; the second was to actively control the spear valves; and the third was to control the braking torque from the generator. For a set system pressure; there is an associated optimal speed for the pelton wheel. The change in flow rates during a wave period is managed by cycling the effective flow area of the spear valve from fully closed to open and back. As the hydraulic power comes onto the pelton wheel it will try and speed up, this is controlled by the flywheel which will store some of the energy, increasing the generator braking torque and by throttling the flow. The effect of throttling the flow has two effects; it slows down the pelton wheel and also diverts some of the flow into an onshore accumulator, this in turn slightly increases the system pressure which increases the water jet velocity to match the

increased speed of the flywheel. Clearly wave power is not constant so every 15 minutes the control system also changes the system pressure to ensure a near optimal hydraulic to electrical conversion is achieved throughout the day.



Turbine Container

There are a number of safety features in the control system. For example, if the pelton wheel over speeds or any of the temperature, vibration or pressure instruments read outside the normal range, all hydraulic power is dumped. Two valves on the main high pressure line open to dump the flow directly to a phreatic tank, bypassing the pelton wheel.

Mechanical To Electrical Conversion

The electrical system provides the mechanical power on the common shaft between the pelton wheel and the generator and the grid connection at EMEC. The electrical energy is transferred to the grid via an 11kV interface at EMEC.

The key components of the electrical power system are; an 11kV breaker & protection, 11kV/400V transformer, a Drive system and G59 protection, a generator and auxiliaries.

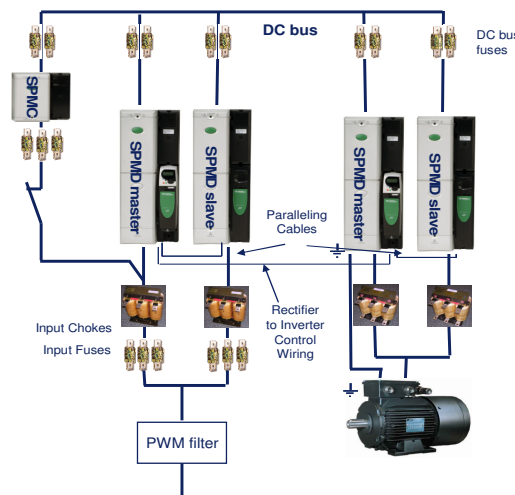
The power conversion system for the Oyster prototype comprises a variable frequency inverter coupled to an induction generator. The primary purpose of this drive is to match the torque/speed characteristics of the Pelton turbine.

The introduction of a flywheel between the pelton wheel and the generator not only stabilises the electrical power generated, but also allows the generator to have a rating of about half the pelton wheel power rating.



Electrical Container

The drive solution comprised of four separate Unidrive modules, two of these providing the variable speed requirements of the generator with the other two providing the grid interface. One advantage of this modular arrangement is that it provides a degree of fault tolerance. i.e. if one of the drive units should fail, the others can continue to operate at a reduced power until repairs can be implemented.



Key Drive System Components

Reliability

It was recognised in the design and procurement process that wherever possible, the equipment must be simple, robust and built from components having inherent suitability for their purpose, using well established technology and equipment. Preferably all components should have been proven in previous operational (although not necessarily similar) applications. The equipment will experience approximately 8 million operations (flow reversals and/or pressure fluctuations) per annum.

Procurement

The Oyster 1 device was procured in four major packages namely; the WEC, the onshore hydroelectric plant, the pipelines to shore and the WEC and foundations installation. There were a large number of smaller packages procuring components to free issue to the larger packages.

Fabrication

The contract for the fabrication and testing of the WEC was awarded to a medium sized offshore oil and gas fabricator based in the East coast of Scotland. The feedback from the fabrication process was that the flap was straightforward to fabricate but the sub-frame and particularly the hinge pin assembly were difficult to fabricate.

Once the fabrication was complete the fabricator also assembled and installed all of the hydraulic systems to enable a complete pressure and mechanical test of the flap and components.

The contract for the detailed design and assembly of the onshore hydroelectric plant was awarded to the New and Renewable Energy Centre (NaREC) based in Blyth. The strategy was to develop a hydro-electric plant that could be housed in two standard 20' containers. The turbine container would house the turbine, pelton wheel and flywheel; the electrical container would house the drive systems and controls. Adopting a container strategy had the benefit that the system could be tested in the factory before being transported to Orkney. The containers would also provide a secure weather tight enclosure on the site.

The pipelines to shore are being installed through directionally drilled holes through the seabed. This was considered to provide the best solution in terms of cost and risk.



Site Layout

Performance

The average power capture of the device deployed adjacent to a typical North Atlantic coast was calculated by taking the performance in each sea multiplied by an occurrence weighting factor. This was determined by weighting each sea to give annual average exploitable incident wave energy of 19 kW/m [1]. This produces an average power output at the hydraulic cylinders of around 200kW. A much more extensive analysis based on 26,500 seas calculated from 19 years of hind cast wave data at the EMEC test site produced a similar performance figure.

As mentioned previously the introduction of the flywheel into the control system for the hydro-electric plant has enabled the rated power of the generator to be optimised and hence Oyster has a relatively high capacity factor compared with other wave capture devices. It is common for devices to be categorised and compared by the rated power as this is generally in the public domain. The better measure is of course the annual energy output or average power as this takes in to account the capture factor and the availability. In the case of Oyster, like most devices, there is not the operating experience to justify the assumptions regarding availability. However, the Oyster offshore WEC has been deliberately designed to be “dumb” and fault tolerant, all of the electronic and control components being placed onshore to simplify operation and maintenance. This factor is considered to improve availability over devices that require intervention offshore.

Finally the other part of the economics of wave energy devices is the capital and operating costs. There is no reliable information on development costs from wave energy developers, however there is a reasonable correlation between weight and capital cost for devices made from similar materials. Comparisons of wave energy devices, that have reached full scale prototype stage, indicate that Oyster has a high average power to weight ratio.

Improvements

With the benefit of the design and construction of Oyster 1 the design of Oyster 2 is underway. The main difference for Oyster 2 will be that it will be designed specifically for an array configuration. The main changes will be; optimising the flap geometry to improve the power capture and assessing different structural, material and foundation systems to reduce capital and installation costs.

Future prospects

The objective is to build wave power stations of 20 to 100MW. Research is ongoing to determine the hydrodynamic performance of clusters of flaps in different geometric patterns, and modelling the array of devices with multiple hydraulic inputs to determine the optimum size and spacing of onshore hydro-electric plants. It was always recognised that the first prototype is the hardest to design and operate as it does not have the benefit of smoothing of the hydraulic flow from multiple units and economies of scale of the onshore hydroelectric plant.

The future development programme also includes wave powered desalination by feeding the high pressure water directly to reverse osmosis tubes.

Concluding remarks

The Oyster WEC has been successfully designed and constructed over the last two years. There is an ongoing programme of testing before the installation and operation of the Oyster WEC next summer.

The device has a number of positive characteristics that make it viable for scaling up to a farm production generating MW's of wave power namely:

- High capture efficiency
- High power to weight ratio
- Fault tolerant
- Designed for extreme seas
- High reliability
- Modular design

Acknowledgements

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