WES KNOWLEDGE CAPTURE

REPORT

WP6 – Maintainability Improvements

OYKNOW-REP-0005

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1. PURPOSE

Aquamarine Power has been asked by Wave Energy Scotland (WES) to produce a series of informative knowledge sharing reports. The contract is to facilitate knowledge sharing within the wave energy sector. The aim is to realise cost and time efficiencies by sharing knowledge and lessons learnt from previous experience so that other companies do not have to go through an exercise of learning the same costly lessons all over again.

Aquamarine Power has accumulated a wealth of valuable knowledge and learning through the design, fabrication, installation and operation of the Oyster 1 and Oyster 800 devices. Aquamarine Power recognise that knowledge sharing is a central component for the successful and timely deployment of wave energy projects. As such, Aquamarine Power is keen to share this knowledge for the benefit of the wider wave energy community.

This is one of a series of 5 reports addressing different topics from the experience and knowledge that Aquamarine Power has gained. The topics under contract with WES are:

1. Offshore operational experience
2. Corrosion & protection in a disturbed water environment
3. Supply chain (marine components)
4. Tank testing of WECs
5. Maintainability improvements from Oyster 1 to Oyster 800

This report covers topic 5 – Maintainability Improvements, as listed above.

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2. LESSONS LEARNT SUMMARY

1. Diver access to the sides of a moving flap can be practically and safely achieved in fairly calm sea conditions, particularly close to the hinge axis. Careful consideration must be given to avoiding any potential entrapment points.
2. Ballasting in a pre-determined direction on a flap type WEC is complex, being affected by the buoyancy and mass distributions, tidal height, wave height, wave period, and PTO forces.
3. Access to all maintainable components must be considered in the design. Vertical access for lifting is of particular importance.
4. Diver access and the space required for tool operation must be considered.
5. Planned cylinder exchanges have been completed successfully and safely using small vessels and bespoke tooling, demonstrating a viable maintenance strategy and proving WEC modularity.
6. Bias valves are an effective means of listing the flap in a chosen direction. Back-up solutions are necessary if biasing is to be relied upon during ballasting.
7. Compartmentalising the WEC ballast chambers allows for a more controllable installation ballasting operation.
8. A modular approach to maintenance of hydraulic system components can be made to work, but in order to be effective the speed of module replacement must be considered through the development of simple interfaces, better access and tooling, and the support of capable vessels and people.
9. Where feasible, and not detrimental to reliability, a ‘nested modular’ approach should be considered in which smaller modules or components are designed to be removable from the larger module.
10. Compact modules with simple interfaces that are well within vessel crane capabilities can be readily exchanged.
11. If a modular maintenance approach is taken, particular attention must be paid to the non-modular items. Their existence should be restricted as far as practicable.
12. High reliability of the non-modular items is critical. Sacrificing reliability for short term cost savings is a mistake.

13. High reliability of fixed pipework systems can be achieved if sufficient attention is paid to material choice, support design, installation accuracy and quality.
14. It is important to consider replacement/maintenance methods for the non-modular items during the design.
15. Tightly packaging cables and hoses through internal conduits will enable them to be well protected, but this makes operations to maintain and replace them challenging.

3. KNOWLEDGE AND LESSONS

Aquamarine Power has been developing the Oyster technology for a period of 10 years. Aquamarine Power has performed extensive R&D activity and built, installed and operated two prototype machines (Oyster 1 and Oyster 800) and more recently carried out two consecutive product improvement campaigns targeting areas from previous 'lessons learnt' activities.

Throughout this period, knowledge and lessons have been learnt relating experience of offshore maintenance operations. The following topics are covered in this report:

1. Overview of maintenance philosophies
2. The Oyster 1 experience
3. Vessels, equipment and people
4. The Oyster 800 experience

4. OVERVIEW OF MAINTENANCE PHILOSOPHIES

Maintenance philosophies have been developed during the years of operating the Oyster 1 and Oyster 800 Wave Energy Convertors (WECs), with optimisations and new conceptual ideas developing from interaction with local suppliers and following a greater understanding of available tooling.

Oyster 1 was a proof of concept machine which demonstrated that it is possible to deliver electricity to the grid. It attracted sufficient investment for the next development stage. It had a short design and operational life, and little consideration was given to maintenance issues during the design. Nevertheless a significant amount of effort was put into maintaining Oyster 1 *in situ*.

Lessons learnt from the operation and maintenance of Oyster 1 were implemented during Oyster 800, although the opportunities to incorporate feedback were limited due to the schedule for the Oyster 800 design and manufacture. Two principal options for maintenance were considered, using modular components or full WEC removal. A modular approach was selected. This decision was heavily influenced by the high cost, extended duration and significant weather restrictions of the Oyster 1 installation.

Maintenance of Oyster 800 has demonstrated that success of the modular approach is dependent on achieving high reliability of the components outside the module. These components cannot always be contained within removable modules. Poor reliability of the systems between modular components has been the greatest challenge to the availability of Oyster 800.

5. THE OYSTER 1 EXPERIENCE

5.1 Maintenance Design Overview

Oyster 1 was a proof of concept machine with a short design life, designed to prove the principles of the oscillating wave surge convertor. As such, the maintenance strategy was not a primary consideration during design. It contained two cylinders which were located at flap quarter points, and were underneath the flap when it was ballasted towards land. It contained a single check valve set, which was positioned with the accumulators in a rigid protection structure at the side of the baseframe. This was also underneath the flap when ballasted to shore. The ballast system for Oyster 1 was distributed along one side of the device and contained both manual and actuated valves.

Late in the manufacturing phase of the Oyster 1 project it was recognised that contingency arrangements needed to be put in place to allow for maintenance access, particularly to the cylinders. A support arrangement (referred to as ‘latch horns’) was installed on the seaward side of the device so that the flap could be opened outwards. These latch horns had a limited capacity, and were not designed for the flap to be ballasted for prolonged periods or in heavy seas in this orientation.

Figure 1 – Key features of Oyster 1 (seaward latch not shown)

5.2 Ballasting

Lessons learnt:

Diver access to the sides of a moving flap can be practically and safely achieved in fairly calm sea conditions, particularly close to the hinge axis. Careful consideration must be given to avoiding any potential entrapment points.

Ballasting in a pre-determined direction on a flap type WEC is complex, being affected by the buoyancy and mass distributions, tidal height, wave height, wave period, and PTO forces.

Discussion:

It was not possible to use the cylinders to lock Oyster 1 in position, due to the very high forces experienced by a stationary flap and hence a ballast system was incorporated to allow the flap to be lowered onto its baseframe. The Oyster 1 ballast system incorporated two options for its operation. The first was by diver connection of hydraulic hoses onto a bulkhead close to the hinge axis. The second was a 'tear away' hydraulic umbilical located on the side of the WEC. This was designed to be accessed and operated from a surface vessel, without the need for divers in the water. This second method was never used in practise.

Diver access to the flap mounted bulkhead was always used for ballasting operations. In practice, access to the side of the moving flap was not as bad as had been anticipated during design. This was in part due to the fact that the diver and the flap both move with similar motion in the water. The risk of sustaining an impact with the flap was assessed as being no worse than that associated with working on a fixed structure in a wave environment. The key risk that had to be managed when accessing a moving flap was entrapment. To be acceptably safe, the equipment design and the diving procedures had to ensure that divers were not placed anywhere near pinch points between the moving flap and the fixed structure.

Control over the ballasting direction (landwards or seawards) was limited. The understanding of what dictates the direction of flap ballasting was initially poorly understood, but improved substantially during the Oyster 1 operations. The mass and buoyancy distributions of the design are significant as are their variation with tidal height. Oyster is far more controllable at low water. Wave height and wave period are also a factor, tending to create a landward bias, but also affecting the range of rotations. PTO forces can influence the ballasting direction. Oyster 1 did not have any control over cylinder pressures, but this was used in the Oyster 800 design to provide a means of controlling the ballasting direction.

5.3 Access Issues

Lessons learnt:

Access to all maintainable components must be considered in the design. Vertical access for lifting is of particular importance.

Diver access and the space required for tool operation must be considered.

Discussion:

The flap could only be ballasted landward in the original design for Oyster 1, which would have meant that it would be folded down over the top of cylinders and valves. Access would not have been possible as a result. This problem was recognised late in the manufacturing phase and a decision was taken to modify the design to provide an alternative support arrangement on the seaward side. This support arrangement (referred to as the ‘latch horns’) was, through necessity, of limited capacity and could not be used for prolonged periods (months) or in heavy seas.

The modified design allowed the cylinders of Oyster 1 to be accessible. The cylinders themselves were not enclosed by surrounding structure or components.

All valves were contained within a permanent protection structure. This resulted in restricted access for divers and diver operated tooling. None of these components were designed for replacement, although the check valves were replaced in the course of necessary maintenance activities. However, the accumulators were unable to be accessed and replaced once they had broken. This had been identified as a risk late in the design process, but the project schedule prevented modifications from being made.

5.4 Cylinder Exchange

Lessons learnt:

Planned cylinder exchanges have been completed successfully and safely using small vessels and bespoke tooling, demonstrating a viable maintenance strategy and proving WEC modularity.

Discussion:

Two successful cylinder exchanges were achieved during the operational life of Oyster 1. Each cylinder weighed 6.5 tonnes. Only the cylinder itself was recovered and replaced during a removal operation.

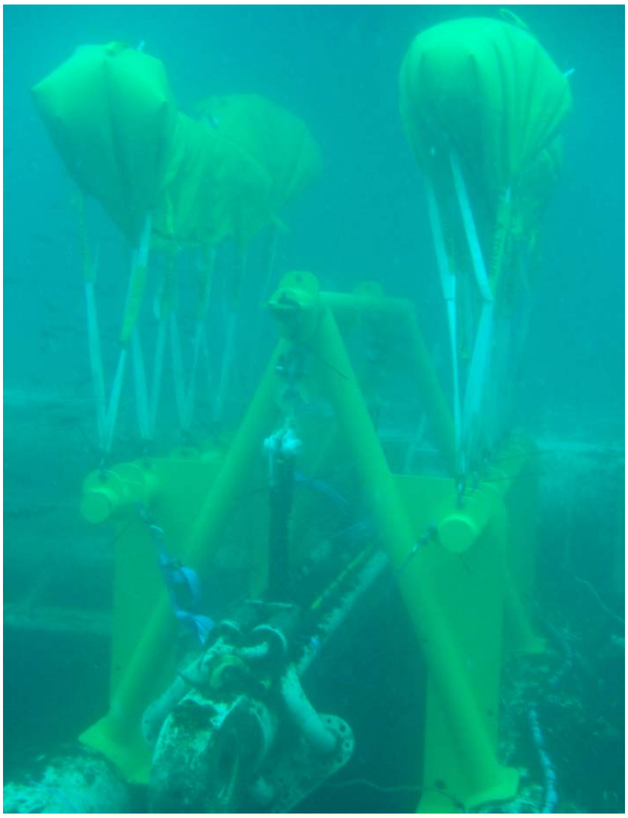

Figure 2 - Oyster 1 cylinder secured in cylinder frame, in preparation for floating to surface

Once the flap was secured in the seaward direction, the hydraulic hoses were removed. A temporary support frame was then lowered onto the tubular baseframe structure. The cylinder was supported from this temporary frame whilst the pins connecting it back to the flap and baseframe were removed. The cylinder was then able to be raised into the frame. Buoyancy bags were used to float the frame and cylinder to the surface, and it was towed back to harbour.

In addition to the float and tow, the two most significant tasks to be completed within the operation were the removal of the pins and disconnecting the hoses. To remove the pins, it was found that pulling was a more effective method than pushing because it tends to be a self-centering action. The pin geometry, stiffness of the structures and the reaction points for the jacking system are all factors that contribute to a smooth removal of tightly toleranced structural pin connections.

The hose interfaces were 4” standard flange connections. This was an awkward and time consuming operation. There was no hose handling mechanism to act as an aid to the diver and tightening the flanges was time consuming.

6. VESSELS, EQUIPMENT AND PEOPLE

6.1 Vessel, Equipment and People Overview

The success, or otherwise, of maintenance activities is heavily affected by the vessels, equipment and people that are available to conduct these tasks. For the WEC designer (at least) two perspectives have to be maintained:

- What resources are available for the immediate development project?
- What resources will be required/could be available for commercial wave energy sites?

These two perspectives can lead to quite different design solutions.

The discussion that follows outlines some of the key learning points from the experience gained over the course of the operation and maintenance of Oyster 1 and Oyster 800.

6.2 Vessels and Weather Considerations

Medium sized multicat vessels are widely available. They provide a fair vessel capability at reasonable cost and are therefore a popular choice for maintenance activities. They have been used for the majority of maintenance activities on the Oyster WECs. Typically their specification features an overall length of around 20-30m, a beam of about 10m and a deck capacity of 100te. They have a powerful bollard pull and are fitted with a variety of winches, cranes and stern and/or bow rollers.

Maintenance activities on Oyster 1 primarily used the workboat, Uskmoor, and then later the multicat, C-Odyssey. These vessels are described in detail in Section 6 of OYKNOW-REP-0001. The specification sheets are readily available online.
(http://www.leaskmarine.com/vessels/mv-uskmoor/item/download/23_0ff95f33e2373cc4b44a96ad8bbc1b51),
(http://www.leaskmarine.com/vessels/mv-c-odyssey/item/download/27_bd099ecaea388f6cea17828b4430b10d).

Maintenance activities on Oyster 800 primarily used the multicats, C-Salvor and C-Odyssey. These vessels are described in detail in Section 6 of OYKNOW-REP-0001. The specification sheet for the C-Salvor is readily available online.
(http://www.leaskmarine.com/vessels/mv-c-salvor/item/download/28_5d4ff3a59d5e1bede2122e7f0298a787). The Uskmoor was used infrequently, and avoided where possible, as there is a reduced deck space and its use is more weather dependant.

At the Billia Croo test site, diving operations typically take place in conditions of <1.5m H_s and <25kts wind speed. The swell varies through the height of the water column. Despite rough surface conditions approaching 1.5m H_s, the diver is generally still able to complete tasks on the seabed, at a depth of 15m.

Activities such as crane operations will usually be affected more severely than diving in rough conditions. A high significant wave height and/or strong winds can create undesirable dynamic load situations on loads suspended from the crane.

6.3 Equipment

A number of tools have been used to assist divers in maintenance activities on the Oyster WECs. These include hand tools, Hydraulic Power Units (HPUs), compressors, hydraulic and pneumatic tooling, and lever hoists.

A detailed description of the offshore equipment used is given in Section 8 of OYKNOW-REP-0001.

6.4 People

During the technology demonstration stage, operation and maintenance tasks will rely heavily on the existing resources and infrastructure close to the offshore test site.

Aquamarine Power has found the Orkney based dive teams to be competent, and to possess many of the required core skills for maintenance activities on a WEC. Their capability has improved significantly over the last five years as developers and the local contractors worked together to resolve problems. It is hoped that this improvement will continue as the industry matures.

Aquamarine Power has established a strong partnership with the Orkney based dive contractor Leask Marine. This partnership has resulted in improvements both in the capability of that dive contractor and in the designs and procedures produced by Aquamarine Power.

Consistency within the dive team has played a significant part in developing skill level and ability. The divers' practical experience of working in the environment around the Oyster devices means that they have many good and novel ideas about how to complete required maintenance activities. Having a consistent group of divers ensures that they are incorporated into the team, and that their feedback and ideas can be captured in a continuous improvement process. A major challenge to maintaining this experience within the team is that higher pay rates are available in other sectors, particularly within oil and gas. Incentivising the more versatile and qualified divers to remain in the team can be beneficial.

During offshore works, Aquamarine Power adopted a policy of placing the engineer responsible for the design on the vessel, in addition to a dive representative. This had a number of benefits including:

- Immediate resolution of any technical issues during the operation
- Emphasis on completing the work to the required quality standard
- Appreciation by the engineer of the practical issues affecting their designs and procedures.
- Effective feedback to improve future designs
- Integration and communication between the offshore team and the engineering team.

For some larger operations, the capacity of locally available onshore cranes could be a limiting factor. On Orkney, Heddles Engineering are able to provide mobile cranes up to 220te capacity. This has not been a restriction for any Oyster-related maintenance operations to date.

During an offshore maintenance programme, there is often a need for the rapid turn-around of fabrications, equipment maintenance, and procurement of additional ancillary items (such as fasteners and hydraulic fittings). Working with local suppliers who are able to facilitate this is extremely valuable to delivery of the project. Tailoring designs to be rapidly produced, using available materials and within the limitations of local manufacturing capability, should be considered, where appropriate, in order to maintain the offshore schedule.

7. THE OYSTER 800 EXPERIENCE

7.1 Maintenance Design Overview

Oyster 800 built upon many of the lessons learnt from maintenance of the Oyster 1 WEC. Specifically, two major features were incorporated into the design:

- The hydraulic system was packaged into replaceable modules.
- A full strength latch system allowed vertical access to the modules with the flap ballasted in the landward direction

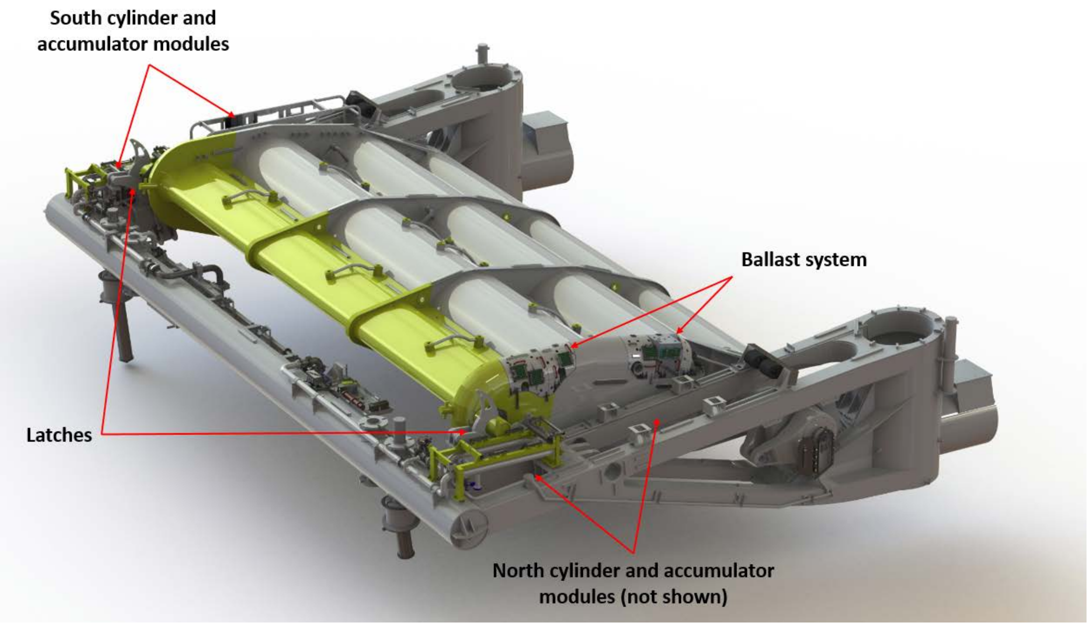

Figure 3 - Location of modular components on Oyster 800 while ballasted

There were 4 principle modules on Oyster 800. These comprised 2 cylinder modules and 2 accumulator modules. These were hydraulically connected back to the fixed pipework on the main baseframe structure using flexible hoses. Each module contained manual isolation systems to prevent contamination during removal/installation.

The fixed pipework system also contained isolation and bypass valves to maintain fluid cleanliness in the wider system during maintenance activities, and to allow independent operation of the PTO systems on either side of the device. These valves could be remotely controlled from shore, which was valuable during pressure testing, commissioning and power production.

A number of distributed systems, including the fixed pipework, C&I and the operational ballast system, did not lend themselves to modularity on Oyster 800 due to their size and accessibility. Activities focusing on these components would be labour intensive and time consuming.

Recovery and installation of the Oyster 800 cylinder modules (23.5te), accumulator modules (4.5te), and other maintenance activities were successfully achieved using the C-Salvor of Leask Marine.

7.2 Ballasting Operations

Lessons Learnt:

Bias valves are an effective means of listing the flap in a chosen direction. Back-up solutions are necessary if biasing is to be relied upon during ballasting.

Compartmentalising the WEC ballast chambers allows for a more controllable installation ballasting operation.

Discussion:

Oyster 800 featured an operational ballast system to enable the flap to be safely latched down to allow maintenance to take place.

During ballasting operations, bias valves on the cylinders would be operated to increase the tendency of the flap to list towards the landward direction. These were moderately effective, but relied upon the cylinders to be functional. Latches on the baseframe secured the flap in position once ballasted down. Oyster 800 also had end stops in the seaward direction, but no seaward latch. As such it was not desirable to ballast in that direction.

The ballasting operation was designed to be controlled from shore, but it was always conducted with a vessel and compressor on station in case of ballasting in the seaward direction. The principal risk during the ballasting procedure came at the point when the flap was at neutral buoyancy. At this time, there was a chance the flap could ‘flip through’ and ballast in the seaward direction. Over time, a procedure was developed to monitor flap movements, tidal height and wave climate during ballasting in order to confirm safe (landward) ballasting.

The ballasting configuration for installation of the WEC differed from the operational ballast system. The horizontal tubular structure was divided internally by bulkheads so that the trim of the floating device could be controlled and the free surface affects within partially pressed up ballast tanks were within manageable limits.

7.3 Cylinder Modules

Lessons learnt:

A modular approach to maintenance of hydraulic system components can be made to work, but in order to be effective the speed of module replacement must be considered through the development of simple interfaces, better access and tooling, and the support of capable vessels and people.

Where feasible, and not detrimental to reliability, a ‘nested modular’ approach should be considered in which smaller modules or components are designed to be removable from the larger module.

Discussion:

Design intent:

Following operation of Oyster 1, the design intent for Oyster 800 was to move as many of the hydraulic components as practicable onto a principal cylinder module. This could then be removed and replaced with a spare to minimise down time. The module contained manual isolation valves, a Pressure Relief Valve (PRV), a bias valve, check valves, instrumentation cables, a junction box and flexible hoses to connect back to the fixed pipework. The check valves were directly mounted to the cylinder, which had an additional benefit of enabling a ‘stiff’ hydraulic system to be created, reducing fatigue in pipework/flexible hoses.

The cylinder and ancillary components were protected by a permanent frame, which would support the module weight, and provide additional protection during installation/removal and transportation. In total, the cylinder module weighed 23.5te, at a size of 4m high x 1.5m wide x 8m long. Once on the back of a trailer, this height was just within the standard height restrictions for road transportation, which is 4.9m for trunk roads. This limit also applies to the Hamnavoe ferry operating between Stromness and the mainland.

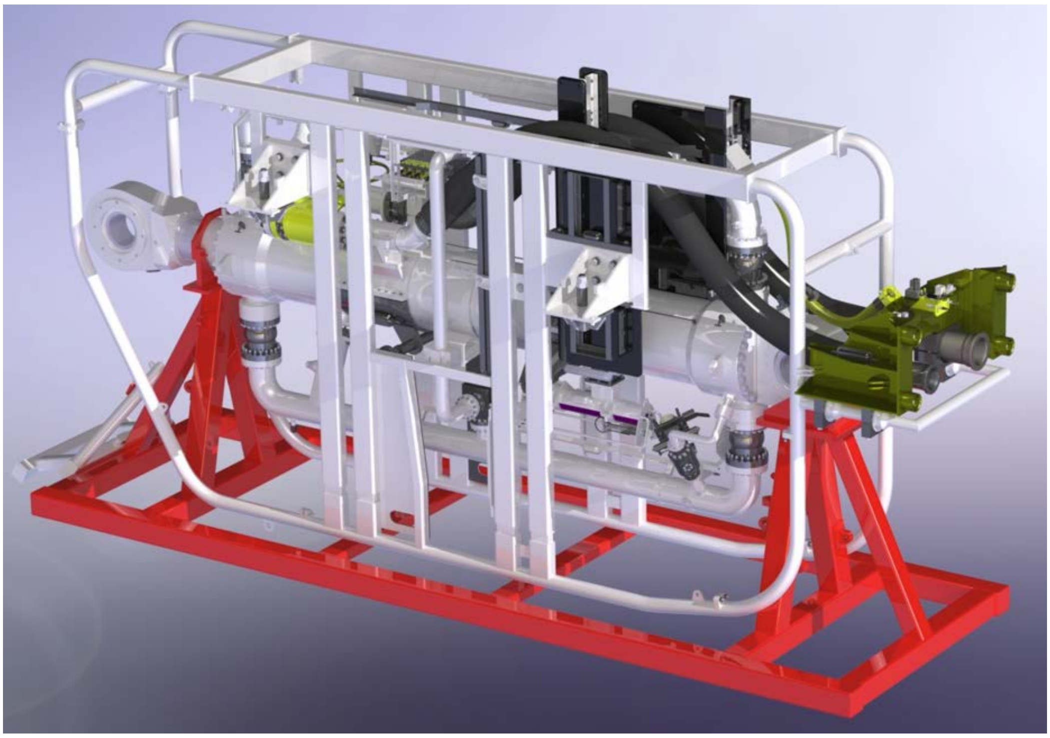

Figure 4 - Oyster 800 cylinder module, mounted on the transportation frame

The module was only just within capacity of available vessel cranes and the offshore operations were therefore highly weather sensitive and reliant on suitable vessels being available. The crane winch is of a lower capacity than the crane itself, and the cylinder removal operation required the crane jib to be lowered into the water to reach the module. Some vessel cranes have sensors at the end of the jib preventing their immersion in water, so this operation is not always possible.

Prior to the first cylinder module operation, trial lifts were completed on the C-Salvor vessel to ensure suitability of the vessel and crane. A scaffold frame mirroring the dimensions of the cylinder module was lifted to assess required crane positioning and to trial deck handling, and a 23te clump weight was also lifted to verify the impact of the load on vessel stability. These trial operations have also been successfully completed with the Voe Viking of Delta Marine, although to date this vessel has not been used on the Oyster site.

The principle drawback of the module was that because of its size, weight and complexity a module replacement was a much longer and weather sensitive task than anticipated. In-situ replacement of smaller units, such as the PRV, had not been considered in the design.

Having a replacement module available is also critical. Although it seems obvious, on this scale it can become a major cost and schedule issue.

Maintenance features:

The cylinder module did contain a number of features which were designed to aid installation/recovery.

Aquamarine Power has had bad experience with plain cylinder clevis pins on a piece of test equipment. The pins stuck in a frame, and then had to be cut out. Following this, the decision was taken to use a device known as a Bondura Bolt (http://bondura.no/) for the principal connection between the cylinder and WEC. The bolt uses tapered cones which are drawn in by screws to create the same effect as an interference fit between the components. This solution was effective, with no issues of pins jamming. However, it did add to complexity and cost. Access to tighten the screws which drew in the tapered cones was difficult. In future developments, it is conceivable that automated tooling could be designed to allow swift removal.

Each Bondura Bolt pins weighs in the region of 350kg. A bespoke tool was developed to pull and push the pins in and out of position. This tool itself weighed in excess of 1te, and required additional temporary support beams to be installed for support. The installation of the support beams and the tool comprised one of the most time consuming parts of the cylinder exchange activity. Pulling and pushing of the pins themselves was very quick and successful.

Figure 5 - Bondura Bolt, secured within the bespoke Bondura Bolt removal tool

The 6” and 8” flexible hose interfaces used Techlok hub type flange connectors to join between components. These were effective, and with only 4 studs were substantially quicker to install/release than a standard flange. No issues were experienced with loosening. Access for tightening was difficult however. The hoses were pre-installed into a hose indexing mechanism on the cylinder module. This held the hose ends in the correct relative position and orientation, and was pulled back by lever hoists or hydraulic cylinders to allow cylinder removal. Its design was successful and effective, but again access was difficult.

The cylinder support frame had to be accurately positioned during installation to prevent clashing during operation. The guidance system consisted of 2 parts. Curved sections on the cylinder support frame guided it against the WEC baseframe, before stabbing guides on the underside of the mechanical fixing points located it into its final position. The initial design also included a larger scale ‘keel’ design, intended to guide the module into place with larger excursions from position (+/- 1m). This was removed during module refurbishments, as it proved to be un-necessary and problematic for transportation.

7.4 Accumulator Modules

Lessons learnt:

Compact modules with simple interfaces that are well within vessel crane capabilities can be readily exchanged.

Discussion:

By comparison with the Oyster 800 cylinder modules, the accumulator modules were relatively compact. The module weighed in at 4.5te, and initially contained Low Pressure (LP) and High Pressure (HP) accumulators. It was well within the crane capacity, and could be guided into place by the diver using a tag line. Simple guidance features and fendering protected components and assisted positioning of the module. Installation and removal was quick and relatively straightforward- it could be expected to take no more than half a day to complete the entire operation. Installation of the module could be completed in 30 minutes. The rest of the time would be spent on installation of the flexihose and flange tightening, an operation that proved time consuming.

Figure 6 - Oyster 800 accumulator module

The module had a minimal number of interfaces. Flexible hoses were again used, with flange connections to the HP and LP fixed pipework and Techlok hub type flanges to connect to the module. The hoses were installed and connected vertically at the flange connection. Hose positioning was readily achieved by connecting a pulling line, passed through the bolt holes on the mating flange, to a lift bag.

Four mechanical fixings were used on each corner to secure the module in position. Vibrations from the baseframe and the module caused these fixings to regularly come loose. Bolted connections are a complex issue on Wave Energy Convertors. Aquamarine Power has spent a lot of time during its PIP+ programme in 2014 developing a robust bolting methodology which gave greater confidence in the integrity of the bolted connection solutions and which will address issues such as this.

7.5 Non-Modular Items

Lessons learnt:

If a modular maintenance approach is taken, particular attention must be paid to the non-modular items. Their extent should be restricted as far as practicable.

High reliability of the non-modular items is critical. Sacrificing reliability for short term cost savings is a mistake.

High reliability of fixed pipework systems can be achieved if sufficient attention is paid to material choice, support design, installation accuracy and quality.

It is important to consider replacement/maintenance methods for the non-modular items during the design.

Tightly packaging cables and hoses through internal conduits will enable them to be well protected, but this makes operations to maintain and replace them challenging.

Discussion:

It is rarely possible to locate every single maintainable item within a module. This was the case with Oyster 800. Poor reliability of these non-modular systems was the greatest challenge to the successful operation of the WEC. Some of the challenges experienced with these systems are described below.

Isolation and flushing systems:

In order to allow for module removal in a distributed hydraulic system, isolation valves are required to be fitted on the 'non-modular' side of the system. These maintain cleanliness of the system, which is important for reliability of internal hydraulic components and seals. Flushing points are also needed to facilitate cleaning of parts of the system which cannot be isolated from seawater ingress.

Both the isolation and flushing systems on Oyster 800 had reliability issues. The valve actuators, purchased based on their price, were of poor quality and were particularly unreliable. These reliability issues are discussed in detail in Section 3.4 of OYKNOW-REP-0003.

Pipework

A distributed pipework system was required on the Oyster 800 concept to transmit hydraulic power from the flap and cylinder modules back onshore.

The High Pressure (HP) pipework that was manufactured from Duplex (S31803) and Carbon Steel (X52) had few reliability issues, apart from limited cases of fasteners coming loose. This is most likely attributable to residual stress in the components caused by their original fit. The Low Pressure (LP) pipework however was manufactured from a variety of materials in order to save manufacturing cost and installation time. Many failures on the LP pipework prevented machine operation. During the PIP+ project in summer 2014, these issues were largely resolved through the installation of large, single piece HDPE pipework sections and more robust pipe clamps.

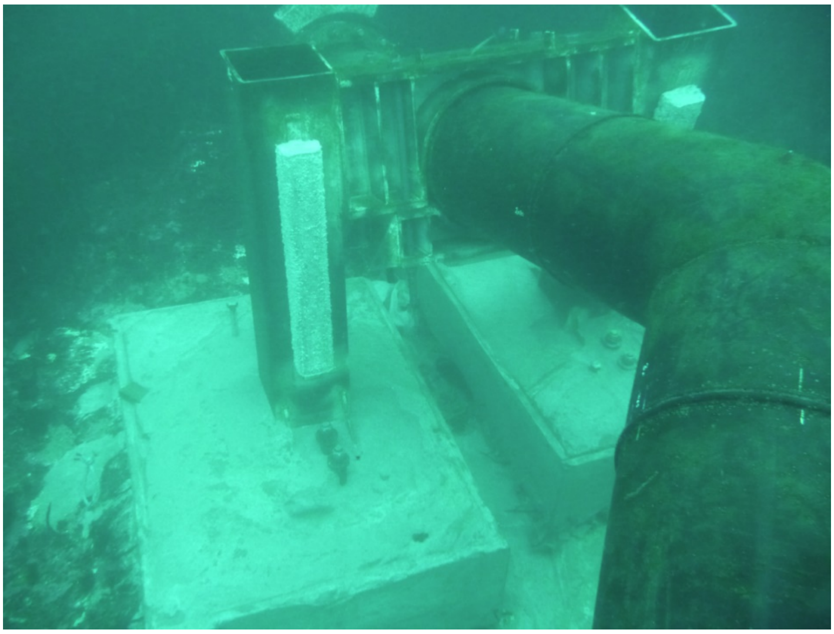

Figure 7 - Improved LP piepwork and pipe clamps, following summer 2014 works

Control and Instrumentation (C&I)

The C&I systems on Oyster 800 by their nature were distributed around the machine. Instruments were required on all 4 modules, and on the flap and baseframe structure to allow control of actuated valves. It is not practical and reliable to use wireless communications from subsea systems, so a fibre optic umbilical cable to shore is also required. Major reliability issues with the C&I have been successfully addressed through detailed design. More robust cable connections, a revised system architecture and modified cable conduits have all contributed towards improved reliability.

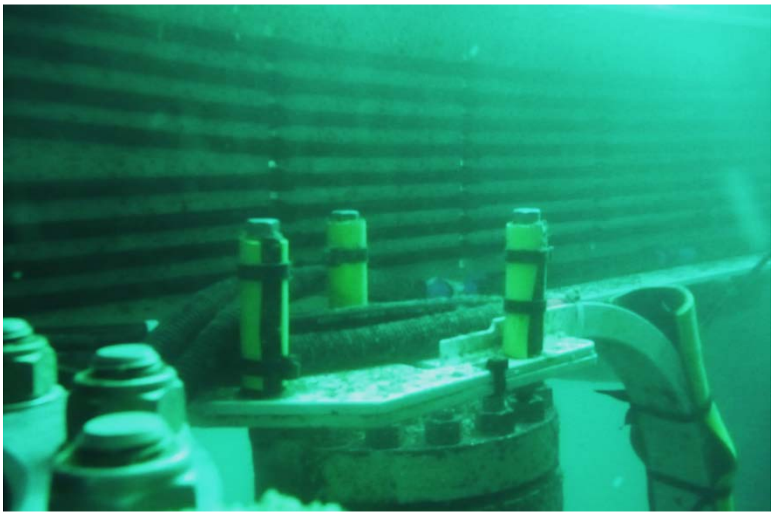

Figure 8 - Cables and hydraulic hoses on robust, open and accessible cable trays

Experience on Oyster 800 has been that robust, open and accessible cable trays proved the most practicable solution for achieving a compromise between survivability and maintenance. Cables could be neatly laid out rather than bundled, ensuring that a single cable can be quickly replaced without needing to release others. C&I improvements are explored in more detail in Section 3.2 of OYKNOW-REP-0003.

Ballast System

The operational ballast system enables the flap to be safely latched down for completion of maintenance activities. The ballast system has to be permanently installed on the flap, with inlet and outlet ports located to suit the ballasting requirements. The system is physically large, with large volume flows, valves and connections. Protection covers are themselves also physically large and their opening is a substantial maintenance task. Since the ballast system is contained within a moving component, it does present a number of challenges. Specific challenges for Oyster 800 included:

- Rotary connection back to the fixed structure
- Positioning hardware in the splash zone
- Preventing bolt loosening
- Balancing protection with accessibility.

The rotary connection carries hydraulic hoses and electrical C&I cables back to the fixed baseframe structure. An energy chain was used on Oyster 800 to provide this connection. The solution was effective, but the implementation of the detail of the design resulted in this being an area of poor reliability. One example is that although hoses were protected, they were not adequately secured along their length, and as a result were able to rub/move against the edges of the protection in extreme wave conditions. Hydraulic fittings are also prone to coming loose under oscillating motion. Fixed bulkheads were installed at either end of the energy chain, which minimised the motions of the hydraulic components and greatly improved reliability. A hydraulic override bulkhead at the bottom of the flap, where motions were less, was readily and safely accessible for divers. This allowed ballast valves to be operated from a Hydraulic Power Unit (HPU) onboard the vessel, if the rotary connection was not functioning.

Within the splash zone, corrosion protection is not as effective. This can lead to corrosion issues, unless very careful consideration is given to material selection. Unprotected 316 Stainless Steel is not adequate in this environment, and has led to poor reliability of hydraulic components.

Corrosion protection issues are discussed in detail in Section 3.3 of OYKNOW-REP-0002. Flap motions and vibrations contribute to effects like bolt loosening on pipework flanges and valve actuators, and should be addressed through design.

Accessibility was an issue, as the Oyster 800 ballast system had to be adequately protected whilst the flap was in operation, but readily accessible for maintenance when the flap was ballasted down. The valves themselves were located within two ‘sea-chests’ on the side of the flap, connected by a small conduit through end profile structure. The small conduit size made the subsea replacement of cables and hoses challenging, as there was no scope to pull through cables with larger, more robust end fittings.

Hinged ‘sea-chest’ hatch covers provide protection, but are in themselves large and heavy so opening them to allow access becomes a significant maintenance activity in its own right. Smaller, inspection hatches, within the main ‘sea chest’ covers allow inspection of the ballast valves and actuators. To be effective, the hatch design needs to consider the size of a dive helmet.