OYSTER 2 PROJECT

TECHNICAL NOTE

OYSTER 2B Flap Shape Selection

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1. INTRODUCTION

Aquamarine Power is currently developing the third iteration of the Oyster Wave Energy Converter. This device is known as Oyster 2B (later, Oyster 801). It will be the second WEC to be installed at the near shore site at Billia Croo, Orkney. It will connect to the same pipeline infrastructure as Oyster 800 (2A), where the single monopile has already been designed and installed using the Oyster 2a load case as outlined in (Ref. [1]). Installation is planned to take place in the summer of 2012.

The purpose of this note is to document the results of tank testing different concepts and the relevant design studies to justify the selection of the final flap geometry to be taken forward to the next phase of the project.

2. PROJECT DEMANDS

2.1 Objectives

The concept was developed with the company's objectives in mind (Ref. [2]). These are based on using the Oyster 800 as a benchmark and in line with the company's ability to demonstrate that the technology can meet Levellised Cost of Electricity (LCOE) figures consistent with the business plan (Ref. [3]);

- An Improvement of 10% Electrical Power over Oyster 800
- Designed, manufactured, procured and installed by summer 2012
- Cost of Power
- Budget

2.2 Gate Review

The concept design studies for Oyster 2B culminated in a gate review conducted on 15th June 2011 that recommended that the design progressed based on the following concepts:

- Glass Reinforced Polymer (GRP) Flap
- Vertical Cylinder Power Take Off (PTO)
- Upright Maintenance Strategy
- Mechanical connection to a pile adapter

2.3 Performance, Cost and Time Line

Due to the manufacturing benefits of GRP over Steel fabrication, there is the ability to produce a flap with a complex asymmetric shape. This enables the addition of several performance enhancing features over the Oyster 800. The initial design as presented at the gate review included these features and can be seen in Table 3 named 'Complex' and came from the hydrodynamic demands of the Functional Specification (Ref. [4]).

Results for the Complex model from tank testing and an Energy Production Estimate (EPE) Lite showed a promising improvement of 7% in electrical performance. However, when considering the other objectives this led to higher tooling and manufacturing costs and extended timelines (Ref. [7]) (see Table 1). Tests also showed that the flap over rotated towards the beach (see Table 4).

In addition a simplified 'box like' shape was presented which led to reduced tooling costs and the associated manufacturing lead time. This was due to its large flat surfaces and symmetry of

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edges. However compared with Oyster 800 the Simplified Box shape had a 1.2% decrease in electrical power thus it failed to meet the performance objective.

Table 1 EPE Lite Electrical Power (Ref. [5])

Flap Shape	Electrical Power (kW)	% Increase Over Oyster 800
Oyster 800	168	-
Complex	180	7%
Simplified	166	-1.2%

It should be noted that the EPE presented here is that for the Oyster 800 concept and is higher than the device as built.

2.4 Flap Shape

Thus the flap shape affects the key objectives. Several further concepts for Oyster 2B were considered to find a compromise between the high performing complex shape and the simplified lower performing shape. These were based on the Simplified Box shape but with single variable changes to highlight which key features (see Table 2) could potentially retain performance. Photos of each concept can be seen below in Table 3.

Table 2 Flap Shape Features

Flap Shape Features	Potential Benefit
Flap Thickness	Reduction in edge vortices and thus a reduction of losses.
End Effectors Shape	Reduction in edge vortices and thus a reduction of losses.
Enhanced Freeboard	Prevents overtopping of the waves, thus increased power capture.
Offset Hinge	Effects the position of buoyancy in still water. Potential for control of the direction of over rotation. Can reduce mean offset landward so reduce overtopping.

Several other characteristics were also considered and verified as they to play an important role in the design of the WEC.

- **Loads** – Oyster 2B attaches to monopile which has been designed and installed. Therefore the Loads must not exceed the piles capacity and the Yaw load case must now be given greater consideration. The critical load is expected to be total fatigue pitch bending at rock level in the pile (i.e. fatigue surge x hinge height + damping torque).
- **Cylinder Geometry** – The full rotation of the flap is dictated by the position and movement of the cylinders and torque arm. Thicker flaps can cause geometrical issues and would need larger cut-outs in the centre of the flap thus increasing complexity of shape and affecting the centre of buoyancy and pitch stiffness.
- **Over Rotation** – Oyster 2B is designed without a latching mechanism; at no point should the flap strike the seabed or over extend past the allowance of the cylinders.

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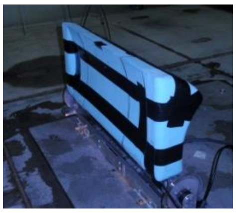
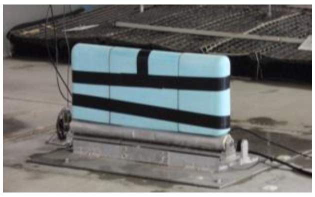
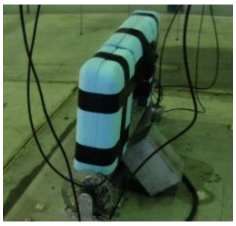
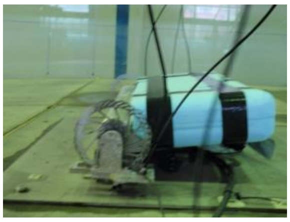
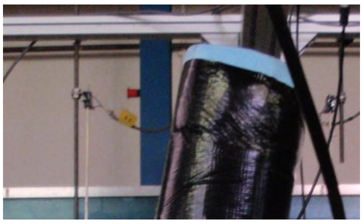
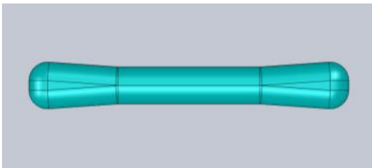
- **Pitch Stiffness** – The GRP flap is inherently light and buoyant, thus the increased volume due to shape would require the addition of ballast through flooding or addition of weights to achieve the optimal pitch stiffness.

Table 3 Concepts Tested (Ref. [5])

Complex		
Simplified	.	
Simplified 4m		
Simplified Enhanced Freeboard		
Simplex 'Bowtie'		
Simplified 3.5m Offset and Enhanced Freeboard		

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3. RESULTS

3.1 Tank Tests

The full results of the tests can be found in (Ref. [5]) and as an overview in Table 4. It can be seen from results that;

- Enhanced freeboard leads to an increase of performance.
- Increased thickness leads to an increase in performance
- The increase of 4m thickness poses an issue with the levels of buoyancy and thus a higher than optimum pitch stiffness. Could be optimised through ballasting.
- Increased thickness leads to greater loads.
- Increased thickness probably rotates further.
- Increased end effectors (Simplex 'Bowtie') leads to greater loads.
- Asymmetric shapes lead to a still water bias potentially effecting extreme rotation.

Table 4: Overview of Tank test results (Ref. [5])

	OY800	Complex	Simple	Simple Enhanced Freeboard	Simplex 'Bowtie'	Simple 4m Thick	Simple 3.5m Offset Hinge, Enhanced Freeboard
Measured Pitch Stiffness @ MWL (MNm/Rad)	13.8	27.0	24.6	22.6	24.5	31.8	23.8
Electrical Power (kW)	168	180	166	171	171	175	172
Mechanical Power (kW)	243	261	241	250	248	253	254
% change from OY800	-	7.1	-1.2	1.8	1.8	4.2	3.6
Max Rotation Towards Beach (Deg)	66.3	82.1	68.9	80	65.5	68.1	68.6
Max Rotation Towards Sea (Deg)	-93.0	-78.5	-78.2	-72.9	-79.4	-76.8	-84.1
Angle offset due to natural buoyancy of the flap (Deg)	1.5	11	5.8	11.6	2.1	5.5	-0.8
Rotational Range (Deg)	159.3	160.6	147.1	152.9	144.9	144.9	152.7
Cylinder Geometry compatible with rotational excursions*	N	N	Y	N	Y	Y	Y

* Assumes geometry allows +80/-90 rotation & 5 degree margin required

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3.2 Manufacturing and Geometry

- Increased thickness leads to higher material costs.
- Tooling costs increase when symmetry is lost.
- Large flat surfaces are preferred over curvature.
- Increased thickness over 3.5m leads to cylinder geometry issues.
- Increased width and end effectors lead to complex geometry and curvature.
  Increased thickness requires flooding of chambers to optimise pitch stiffness.

Table 5: Manufacturing Costs (Ref. [7])

	Complex	Simple	Simple Enhanced Freeboard	Simplex 'Bowtie'	Simple 4m Thick	Simple 3.5m Offset Hinge, Enhanced Freeboard
FRP manufacturing cost	£1,200k	£1,100k	£1,100k	£1,150k	£1,150k	£1,150k
Tooling Costs	£750k	£200k	£250k	£350k	£250k	£300k

3.3 Pile Fatigue Capacity

The OY-2b monopile was designed in December 2010 based on the OY-2a loads as defined in OY02-DES-ST-APL-TN-0010 - Updated Loads on Oyster 2 in Performance and Fatigue Seas – B1.

Comparing these load cases and the FEED design loads which have been derived for the OY-2b flap (Ref: OY02b-DES-ST-APL-SPEC-0015 - OY2b Operational Load Data for FEED), there is a 12% increase in effective fatigue surge. This is based on the load data from concept level testing of the complex FRP shape.

However, the depth of the hinge from the rock at the pile location is 4.32m (compared to a worst case design-value of 5.0m), and this difference along with a small reduction in RMS damping torque will give a total fatigue pitch bending of the pile where it enters the rock similar to the design value.

This quick assessment would indicate the pile capacity should just be adequate for the complex geometry and that any shapes giving a higher fatigue load range will present a problem. The table below extracted from Ref [5] shows that this would rule out the simplified 4m thick flap option:

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Table 6: Effective Fatigue Surge Loads (Ref. [5])

	Complex	Simple	Simple Enhanced Freeboard	Simplex 'Bowtie'	Simple 4m Thick	Simple 3.5m Offset Hinge, Enhanced Freeboard
Average Effective Surge Load Range (MN)	5.70	n/a	5.24	5.74	6.07	5.31

Given how close this rough assessment indicates we are to the pile designed capacity and the approximations inherent in the assessment it would be prudent to select one of the concepts with a lower effective fatigue surge range or to carry out a more detailed assessment of the pile capacity.

3.4 Extreme Loads

Extreme loads tend not to drive the design; however if and when they increase significantly they can become a driving factor. The extreme heave and surge loads on the Simple 4m thick flap shape are much larger than the other concepts (+110% and +22% of the complex shape max surge and heave respectively), Ref [5]. These extreme loads would likely drive the design and represent a problem for the monopile capacity.

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4. SUMMARY

Further discussions with Research and Development, Engineering and Optima Projects led to the final test concept incorporating the enhanced freeboard, an increased thickness and an offset hinge to counteract rotation towards the beach (Simple 3.5m Offset, Enhanced Freeboard). This showed the most promising performance results with further gains possible through the optimisation of the pitch stiffness. A more detailed design study showed that the concept should have a MWL pitch stiffness of 26.95MNm/rad as opposed to 23.8MNm/rad pitch stiffness tested.

However this concept fails to meet the objectives as outlined in 2.1 with only a 3.6% power increase on Oyster 800. Table 7 summarises the key results and financial implications of each concept.

Table 7: Summary

	Complex	Simple	Simple Enhanced Freeboard	Simplex 'Bowtie'	Simple 4m Thick	Simple 3.5m Offset Hinge, Enhanced Freeboard
% Power change from OY800	7.1	-1.2	1.8	1.8	4.2	3.6
Max Rotation Towards Beach (Deg)	82.1	68.9	80	65.5	68.1	68.6
Max Rotation Towards Sea (Deg)	-78.5	-78.2	-72.9	-79.4	-76.8	-84.1
Annual revenue (£k) [8] (change relative to 'Complex' concept)	0	-27	-18	-18	-10	-15
NPV (£k) [8] (change relative to 'Complex' concept)	0	431	456	304	472	375
LCOE (£/MWh) [8] (change relative to 'Complex' concept)	0	55	18	34	-11	18
CAPEX (£k) [8] (change relative to 'Complex' concept)	0	-650	-600	-450	-550	-500
Schedule Impact (Weeks)	0	-10	-8	-6	-8	-8

A further study (Ref. [6]) showed that if the hinge of the Oyster is lowered by 1m it could lead to an increase of 0-4.7% in electrical power. This coupled with the geometry shape changes show a more promising result. However it must be noted that only the Complex shape would achieve the 10% increase in power and that these percentages cannot be simply added. As the pile is already installed there would need to be a study into the viability of lowering the hinge with regards to loads and other practicalities.

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4.1 Flap Shape Meeting 26/07/2011

The results were presented and discussed. The 3 main concepts were considered as the alternatives showed step changes between the extremes to regain the performance. The following scoring matrix was applied and agreed upon. Each concept was scored from 1-5 (5 being best) for the following project drivers as shown in Table 8.

Table 8: Scoring Matrix

	Complex	Simple	Simple 3.5m Offset Hinge, Enhanced Freeboard
Performance	4	1	2
LCOE	3	1	2
Budget	1	4	3
Schedule	1	3	3
Engineering Risk	2	4	4
Totals	**11**	**13**	**14**

Finally, hinge height was discussed to increase the use of the water column and thus increase the performance. But this was discarded as it highlighted engineering concerns with the schedule, mechanical connection & pile design and bathymetry. An alternative option was discussed, which was to increase flap width and thus flap area.

It was agreed upon that the FEED stage of the project must continue with the Simple 3.5m Offset Flap. This enables the next step of tank testing to begin and the progression of the respective suppliers/contractors.

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5. REFERENCES

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2 110414 Corporate objectives 2011-12.pdf
3 091007 Commercial Evolution of the Oyster Device v7 0 APL-RD EM 02-REP-0002 A22b.docx
4 OY02b-DES-ST-APL-SPEC-0006 - Flap Hydrodynamic Functional Specification - A3.pdf
5 110707 - Oyster 2B Composite Linear PTO - Concepts Summary – APL-RD.FDR.03-EXR-0072 - A4.xlsx
6 110720 Parameter Map Hinge Height Study - APL-RD.FDR.04-REP-0096 - A1.docx
7 110615 Composites - Optima Projects 2B Gate Review.pptx
8 Oyster 2b flap shape selection A2.xls – Garth Bryans

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