Project Know-How

Aquamarine Power Exploratory Research

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Abstract

In 2015, Aquamarine Power Limited (APL), developer of the Oyster 1 and Oyster 800 wave energy converters, went into administration and their intellectual property (IP) was acquired by Wave Energy Scotland Limited (WES).

The IP contained a significant body of information from exploratory small-scale tank tests completed during the company's trading history. This information exists across multiple internal documents which are not suitable for public publication.

Nine key research topics, which relate to the exploratory WEC research completed by APL for flap-type Oscillating Wave Surge Converter devices, have been identified and are summarised and independently presented within this report which has been prepared on behalf of WES by APL's former head of R&D (now of Cerebreon Technologies Limited).

In each case, a detailed narrative is provided which explains: the rationale behind the research investigation; qualitative and quantitative conclusions; references to supporting and publicly available information; and the reasoning behind any decisions made by the company following on from the research. The information is being shared now for the benefit to the wider wave energy sector, and to provide additional information to technology developers. Whilst the numerical results of the APL research may be unique based on their particular version of the OWSC technology, others should find this information of use.

Executive Summary

This report aims to communicate the key findings and lessons learnt from some of Aquamarine Power's exploratory research activities into bottom-hinged, flap-type WECs. The research was centred about the company's Oyster device. As such the results are representative of this type of device. There is no guarantee that the same conclusions can be applied directly to different technologies.

Nine key topics have been identified and are presented as independent sections of this report. The topics discussed and the single most significant conclusion associated with each are as follows:

1. **The influence a gap underneath the hinge line of the flap has on power performance.**
   Power capture is reduced by circa 15%-25% if a gap is presented underneath the hinge line of the flap. This is due to a reduction in the incident wave torque induced onto the flap.

2. **The influence the freeboard has on the power and loading of a pitching flap.**
   A flap which is permanently submerged captures circa 30% less power than a flap which has a positive freeboard piercing the water surface.

3. **Operation of a flap in deeper water.**
   Bottom hinged, flap-type devices are better suited to shallower waters (the same is also true for top-hinged flaps). Within practical engineering constraints, a water depth of circa 12m-16m would appear to be optimal for power capture.

4. **Influence of 'end-effectors' on power performance.**
   Large, rounded, protruding structures attached at the ends of a flap (i.e. 'end-effectors') can improve power capture performance by up to 15%. This is due to a reduction in fluid turbulent/vortex losses at the edges of the flap and an increase in the incident wave torque. The performance improvement is not accompanied by a proportional increase in the foundation loads experienced by the device.

5. **Using elastomeric materials to replace the structural buoyancy of the flap.**
   It appears feasible to design a flap-type WEC concept where the restoring moment is provided by an elastomeric hinge instead of through inherent buoyancy of the flap. However, there is a significant increase in the forces that must be reacted by the substructure/foundations.

6. **Determining the impact of bio-fouling on the flaps power performance.**
   Significant levels of bio-fouling (e.g. large colonisation of kelp) on the seaward face of the flap can reduce power capture by circa 15%.

7. **Approaches of modelling wave slam on pitching flap-type devices.**
   Wave slam on the face of the flap is a complex multi-faceted phenomenon. Quantification of the physical process at play requires several research techniques which include: high-end CFD, highly instrumented wave tank tests and model FEA. High-speed camera images of the wave tank tests were found to be one of the single most useful information sources to gain insights and an understanding of the complex process. In addition, the highly non-linear slam

event falls well within the remit of CFD techniques and the short duration of the process is also compatible with the high computational effort required from these techniques.

8. **Using a compliant fabric material as the main structural body of a flap-type device.**
   Using a fabric material is not a realistic or practical way to construct a flap-type WEC, for the purpose of power production.

9. **A multi-body or modular version of a flap-type device.**
   A modular flap-type device appears to be a very feasible WEC concept which offers a comparable power capture to a large rigid flap, but experiences significantly smaller parasitic foundation loads. In addition, cost saving opportunities also exist in the scale manufacturing of small modular units as well and transport and offshore handling, when compared to a single large flap device.

As well as the specific conclusions from each research topic, some overarching lessons which span across all research activities were also identified through Aquamarine Power's experience. The most significant of these are:

- **Management of the WEC design as it evolves from R&D to an engineering reality.**

  There is an iterative loop between practical engineering design and initial concept specification before a WEC structure will become a reality. Oversight of the functional requirements, commercial constraints and interdependencies must be stringently monitored and held steadfast during this iterative cycle. It can be detrimental to pursue overly elaborate WEC structures, sub-systems or modes of operation as the probability of commercially achieving these in reality is much lower.

  An example of where such a process was not executed successfully was in the end-effector design on the Oyster800 device, as discussed in Section [C3] of this report.

  A formal decision was made by Aquamarine Power to include rounded end-effectors to the device, but their specific shape and size evolved as the detail engineering design progressed to accommodate interfacing subsystems and to minimise manufacturing complexity and cost. As a result, the shape which was ultimately installed on Oyster 800 was far from optimal from a hydrodynamic perspective, yet the cost of fabrication remained high.

- **In experimental wave tank tests, it can be more beneficial to design and make multiple scale WEC models with a focused functionality rather than a single 'all encompassing' model.**

  The natural desire is to attempt to build a single 'one fits all' experimental model which is capable of recording all information from a tank test, e.g. power capture properties, extreme wave loads, installation loads and dynamics etc. However, the parts and subsystems necessary for one set of tests can possibly distort and hinder the quality of the result if the model is used for a different classification of tests. For example, recording the power take-off signal of a WEC usually involves some form of force sensor or strain gauged element within the model. If this same model is used for extreme wave loading tests (where the power take-off may not be a factor) then this force sensor or gauged element can introduce an unrealistic/unnecessary level of compliance within the model which can distort the extreme loading results. Thus tailoring (limiting if necessary) the model design and functionality to the priority objectives of the particular test can improve the quality of the results.

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1 Purpose

This document collates and summarises the key activities and conclusions of the exploratory Wave Energy Converter (WEC) research conducted by Aquamarine Power Ltd. (APL). During its trading history (2006 – 2015) APL accumulated a wealth of valuable knowledge and learning through their R&D activities. Wave Energy Scotland (WES) has since taken ownership of the Intellectual Property assets of the company and wish to capture knowledge from targeted topics where the information/research exists but it is not in a readily publishable form. By collating this information and disseminating it to the wider wave energy and marine research communities, there is the opportunity to learn, build upon and add clarity to the research completed by Aquamarine Power.

2 Background Information

Aquamarine Power Ltd was a wave energy company who developed a wave energy converter called Oyster. The Oyster system consisted of a WEC located in shallow water close to the shore, with a bottom-hinged, surface-piercing flap which oscillated due to wave action. Double acting pistons on each side of the WEC pumped water through a high pressure pipeline back to shore, where high pressure water drove a Pelton wheel turbine connected to an electrical generator. The flow from the Pelton wheel discharged to a header tank and returned to the WEC via a low pressure return pipeline.

APL deployed a full-scale 315 kW Oyster 1 system at the European Marine Energy Centre (EMEC) in August 2009, followed by a second generation machine rated at 800kW, Oyster800, in August 2011.

APL ceased trading in November 2015 and the intellectual property was acquired by WES.

In parallel with the technology development of Oyster, APL continuously conducted exploratory research into associated and novel topics relating to flay-type WECs. APL had a longstanding relationship with Queen’s University Belfast (QUB) and the core of the APL R&D team were based permanently at the university’s experimental wave tank facility in Belfast. APL also established strong collaborative partnerships with other academic institutes who supported the research into flap-type WECs. For the topics discussed in this report the main collaborative partners were:

- Queen’s University Belfast (QUB)
- Hamburg University of Technology (TUHH)
- University College Dublin (UCD)
- Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE)

A basic outline of the fundamental hydrodynamic principles of a flap-type device (which is regularly classified as an Oscillating Wave Surge Converter (OWSC)) is presented in Section 3. It is advised that the reader is familiar with the operating principles of a flap-type device prior to reviewing the other topics presented in this report.

3 OWSC Prerequisite Information

The governing hydrodynamics of a WEC exploiting the surge component of the waves, i.e. an Oscillating Wave Surge Converter (OWSC) and/or pitching flap-type device, is fundamentally different to that operating in the heaving direction. Folley *et al* ([R1]) illustrates these differences from first principles beautifully. It is strongly recommended that this manuscript is reviewed as a prerequisite by those not well-versed in OWSC hydrodynamics. Most of the APL work summarised in this document assumes this fundamental level of understanding *a priori*.

In summary, the key principles to understand are:

- Surging and pitching WECs are wave-force dominated devices – In general, the more of an obstacle the structure can be to the incident waves the better it will be at capturing power.
- For a surface-piercing structure, the wave force acting on the device increases as the square of the structure width. This is due to the compounding effect of a larger surface area on which the incident wave force can act (Froude-Krylov force) and an increased mass of water that must be accelerated around the structure/obstacle (diffraction force).
- An OWSC will capture more power and become more efficient as its width increases from small to large. This is true up until an optimal size, above which the efficiency reduces again due to the onset of the 'terminator' effect, where the device essentially acts like a 2D body.
- WECs operating in surge have naturally a very broad-banded frequency response. As such, they are quite insensitive (in comparison to an equivalent heaving WEC) to tuning effects.

As might be expected, these fundamental principles were well understood by APL and useful narratives about the research investigations and high-level philosophies behind the Oyster design are summarised in Henry *et al.* [R2] and Whittaker *et al.* [R3]. APL's research concluded that the optimal width (in terms of power capture efficiency) of a nearshore, bottom-hinged, surface-piercing, flap-type WEC is in the range of 22m-28m. Unless otherwise stated, the width of the device discussed in this report is taken to be 26m and the installed water depth 13.4m.

In addition, UCD (one of APL's academic partners) has published a summary review paper, [R4], of all the research they conducted on OWSC's. The key topics explored are explicitly discussed in the paper, but it also acts as an excellent reference source for other information and published papers relating to OWSC. The reader may also be interested in reviewing this manuscript to get a broader understanding of OWSC's and the research that has been conducted and published on this concept.

3.1 References

[R1]. Folley, M., Henry, A. and Whittaker, T., (2015) "Contrasting the Hydrodynamics of Heaving and Surging Wave Energy Converters", *11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France.*

[R2]. A. Henry, K. Doherty, L. Cameron, T. Whittaker and R. Doherty, (2010) "Advances in the design of the Oyster wave energy converter", *Marine and Offshore Renewable Energy Conference (RINA)*.

[R3]. T. Whittaker and M. Folley, (2012) "Nearshore Oscillating Wave Surge Converters and the Development of Oyster", *Philosophical Transactions of the Royal Society A,* Vol. 370, pp. 345-364.

[R4]. Dias, F., *et al*, (2017), "Analytical and Computational Modelling for Wave Energy Systems: the Example of Oscillating Wave Surge Converters", *Acta Mech. Sin. 33(4), pp. 647-662*

4 Report Scope and Structure

From the range of research conducted by APL and associated partners, nine key topics have been identified for review and discussion in this report. They are:

1. The influence a gap underneath the hinge line of the flap has on power performance.
2. The influence the freeboard has on the power and loading of a pitching flap.
3. Operation of a flap in deeper water.
4. Influence of 'end-effectors' on power performance.
5. Using elastomeric materials to replace the structural buoyancy of the flap.
6. Determining the impact of bio-fouling on the flaps power performance.
7. Approaches of modelling wave slam on pitching flap-type devices.
8. Using a compliant fabric material as the main structural body of a flap-type device.
9. A multi-body or modular version of a flap-type device.

Each of these topics is discussed separately in the subsequent sections of this report. The information provided on each topic is structured as follows:

- The research hypothesis or motivation for investigating the topic.
- Summary of the type of research activities conducted.
- Commercial and/or other external influences on the technical research programme.
- Key qualitative and quantitative results and conclusions of the research.
- Outcomes and company decisions following the research.
- References to the supporting reports and information.

For the majority of the topics presented, the quantity which was assessed as a pseudo-metric for the LCOE was the power capture performance of the WEC. This was a common approach adopted by many historic R&D programmes. However, it is recognised that focusing only on power capture is a narrow and often restrictive approach of estimating the commercial feasibility of a WEC concept. LCOE is influenced by the four key metrics: Performance; Availability; Survivability; and Affordability. As such, WEC concepts can exits with a lower power capture performance but improved LCOE. Thus, the isolated power capture results presented in this report should be interpreted in the wider context of the overall LCOE potential of the WEC.

It should be noted that although WES have acquired the intellectual property of APL (which includes the company's internal research reports) they do not necessarily own or have the right to distribute the research reports of APL's collaborative partners. Thus, not all references may be freely available through WES.

5 (A) Influence of a Gap Underneath the Flap

5.1 Research Hypothesis or Motivation

The hydrodynamic principles of a pitching flap indicate that the more of an obstacle the device can be to the incoming waves, the greater potential it has at absorbing more power. Having a gap underneath the hinge line of the flap presents an easier 'route' for the incident fluid/energy to by-pass the device, thus negatively impacting the power capture performance of the flap, see Figure 1. Typical 'gap blockers' are either built from the seabed upwards towards the flap, as illustrated in Figure 1, or else from the flap downwards towards the seabed.

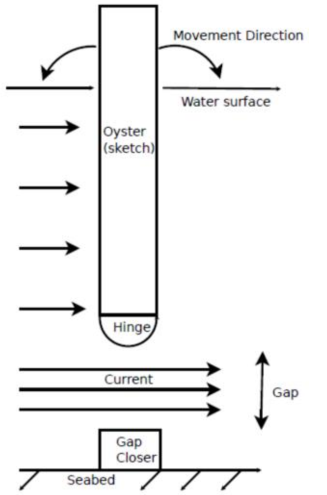


Figure 1. Illustration of a flap with a gap under the hinge line

5.2 Year and Research Activity

- **2008 – Ref. [A1] – Experimental wave tank testing of a 20th scale pitching flap.**

Experimental wave tank tests were conducted on a 12m wide flap at 20th scale in the wave tank facility at QUB. Two device configurations were tested: Figure 2(a) a 12m wide rectangular flap described in the reference as the baseline design; Figure 2(b) the same 12m flap with protruding, rounded 'end-effectors' (discussed in Section [C3]). For both configurations, the flap had a hinge height of 2m from the tank floor and it was tested with and without a 1.5m gap underneath the hinge.

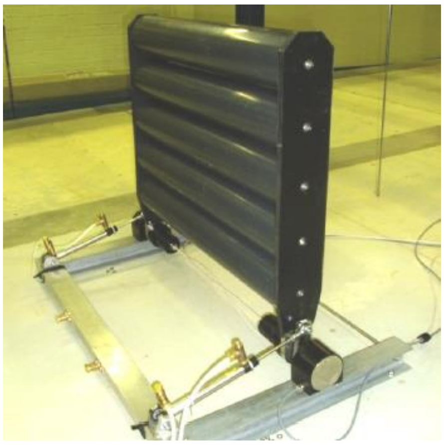
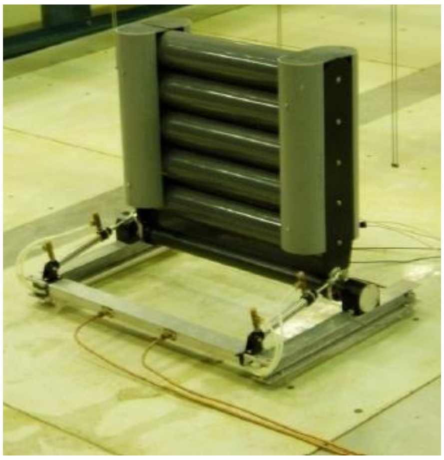
(a)  (b) 

Figure 2. (a) 12m wide baseline flap design. (b) 12 wide flap with 'end-effectors'. Both photographs show the flap configurations with a 1.5m gap present under the hinge.

Each flap configuration (with and without a gap) was tested in 16 irregular sea states created with a Bretschneider energy spectrum. The PTO damping was optimised in each sea state to achieve the maximum power capture. The sea states cover a wave energy period (T_e) range of 7s – 13s and a significant wave height (H_s) range of 1.5m – 4.7m. A frequency of occurrence weighting is given to each sea state so that the set of 16 seas represent a typical North Atlantic nearshore site with an annual average incident wave power of 19kW/m.

2008 – Ref. [A2] – Calculation of incident wave torque on a flap using WAMIT

A short numerical study where the incident wave torque on a 18m wide flap is calculated using WAMIT (a Boundary Element Method (BEM) code). Several gap sizes were assumed from 0m (i.e. no gap) to 2.88m. For each gap size, two scenarios were considered: the first is when the gap was located immediately below the hinge line, i.e. a gap blocking structure partially extends from the seabed towards the flap hinge; the second is where the gap is located at the seabed, i.e. the gap blocking structure partially extends downward from the hinge towards the seabed.

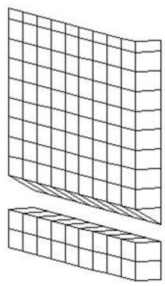


Figure 3. Flap geometry with a gap immediately under the hinge

2010 – Ref. [A3] – Experimental wave tank testing of a 25th scale Oyster800 model

Experimental testing of a 25th scale model of the Oyster800 device, which was installed at EMEC. The device was tested with and without a 1.25m gap under the hinge line. In each case, 15 irregular sea states were used representative of the nearshore site at EMEC. The PTO damping was 'optimised' in every sea state up to a mechanical torque limit of 8MNm, which was reflective of the capacity of the real Oyster800 PTO system. An interpolation algorithm was then used over the 15 'optimal' mechanical power values to get a full device power matrix across a wider H_s – T_m range (significant wave height – mean wave period). This power matrix was then multiplied by an EMEC frequency of occurrence scatter matrix to achieve an annual average mechanical power value. The annual average power of the device with and without a 1.25m gap was compared.

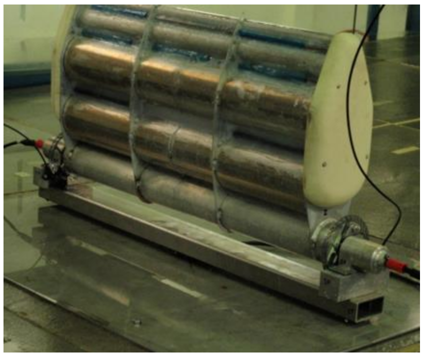


Figure 4. 25th scale Oyster800 model

All tests were conducted at QUB's wave tank facility and in this report the device is referred to as Oyster2a which was a preliminary name for the Oyster800 device.

2010 – Ref. [A4] – Numerical hydrodynamic modelling of different gap sizes

Numerical modelling of the Oyster800 system using a coupled hydrodynamic-hydraulic model in 47 different irregular sea states. The distribution of these seas completely covered the EMEC wave resource scatter matrix. In the numerical model, the hydraulic circuit was that installed in the Oyster800 system and the hydraulic system pressure was varied until the maximum electrical power is generated in each sea (as opposed to optimising the mechanical/hydrodynamic power captured by the device which may be at a slightly different pressure

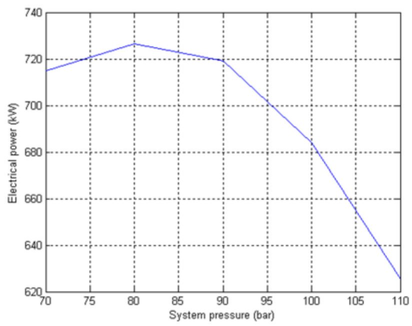


Figure 5. Optimisation of electrical power in a sea state.

setting). Three gap sizes, immediately under the hinge line, were investigated: a 0m gap (i.e. no gap), a 1.25m gap; and a 2.5m gap. In each case an annual average electrical and mechanical power capture value was obtained and compared for each gap size scenario.

- **2011 – Ref. [A5] - CFD simulations of a fixed flap using OpenFOAM. Preliminary study.**

3D Computation Fluid Dynamic (CFD) simulations were performed on a simplified flap structure with and without a gap present under the hinge line. Figure 6 shows the geometry used where the red body represents the gap blocking structure, the blue and green bodies represent the flap (the hinge line is the centre of the green cylinder). In the simulations, the flap was held stationary in the vertical position and a simple monochromatic wave was incident on the device. The fluid pressure field, flow velocity and overall surge force on the stationary flap were examined. This preliminary work acted as a pre-cursor to a more detailed CFD study discussed next (Ref. [A6]).

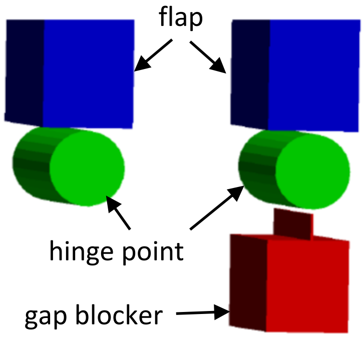


Figure 6. Simplified flap geometry

- **2012 – Ref. [A6] - CFD simulations of a fixed flap using OpenFOAM.**

Following on from previous work (see [A5]), more detailed 3D CFD simulations and analysis were conducted on a vertically stationary flap. Various gap sizes under the hinge line were investigated under three different monochromatic wave conditions. The flow field conditions surrounding the device in each case were examined in detail and linked to the wave torque induced onto the flap in each case. Some novel ideas for gap blocking structures were also suggested and simulated.

5.3 External Influences on the Research Programme

Two of the research investigations were done as part of an academic programme. These were: a QUB Ph.D. thesis (Ref. [A1]); and a TUHH Bachelor Thesis (Ref. [A6]) coordinated by APL under a 6-month internship.

The vested interested of APL to accurately quantify the impact the gap has on the annual power performance of the Oyster device influenced the technical direction of the research.

5.4 Results and Conclusions

1. **In general, the annual average mechanical power capture of a flap is reduced by circa 15%-25% if there is a gap immediately underneath the hinge line of the flap in the size range of 1.25m-2.5m respectively.**

   This result has been consistently quantified in irregular sea-state tests by independent studies [A1], [A3] and [A4], despite using different testing conditions and flap configurations/geometry.

2. **The loss in power capture is directly attributed to a reduction in wave torque induced onto the device, which is the driving force of a pitching flap-type WEC.**

   - Evidence reported in [A1] and [A6] (and also undocumented experienced of APL staff) shows a 1-to-1 relationship (or slightly larger at 1-to-1.15) between the change in wave torque magnitude induced onto the flap and the power captured by the flap.

   - Detailed CFD investigations conducted by [A5] on a vertically fixed/stationary flap, show that the gap allows much greater fluid flow underneath the flap. This easier flow path results in a smaller pressure differential between the front and back face of the flap. This in turn reduces the wave torque induced on the device. A snap shot of the flow velocity and the pressure field around the device are shown in Figure 7 and Figure 8 respectively, when the gap is both present and blocked. (Note: for computational meshing purposes, there was always a tiny space present between the hinge of the device and the gap blocking structure).

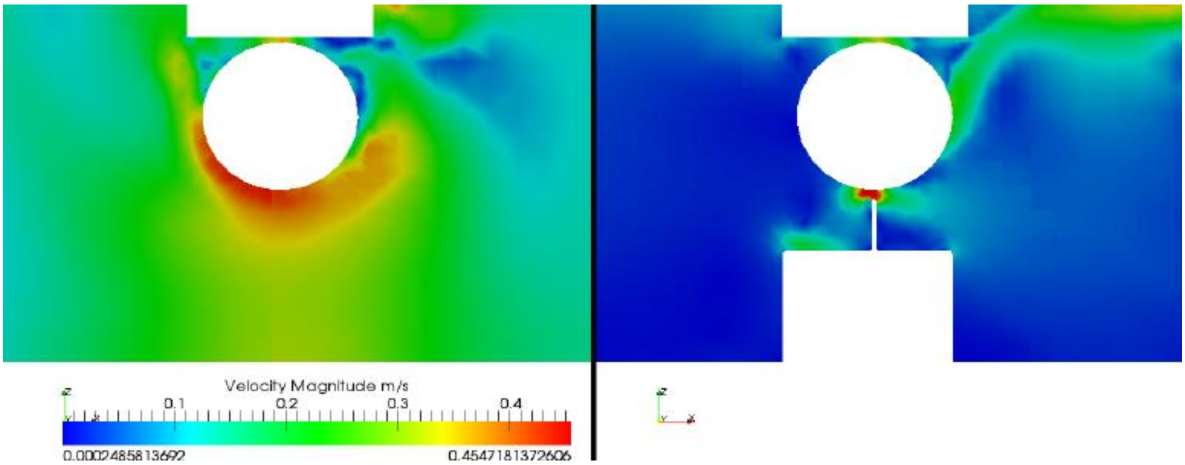


Figure 7. Flow velocity around the hinge area of the flap with: (left) a full gap, (right) a gap blocking structure present.

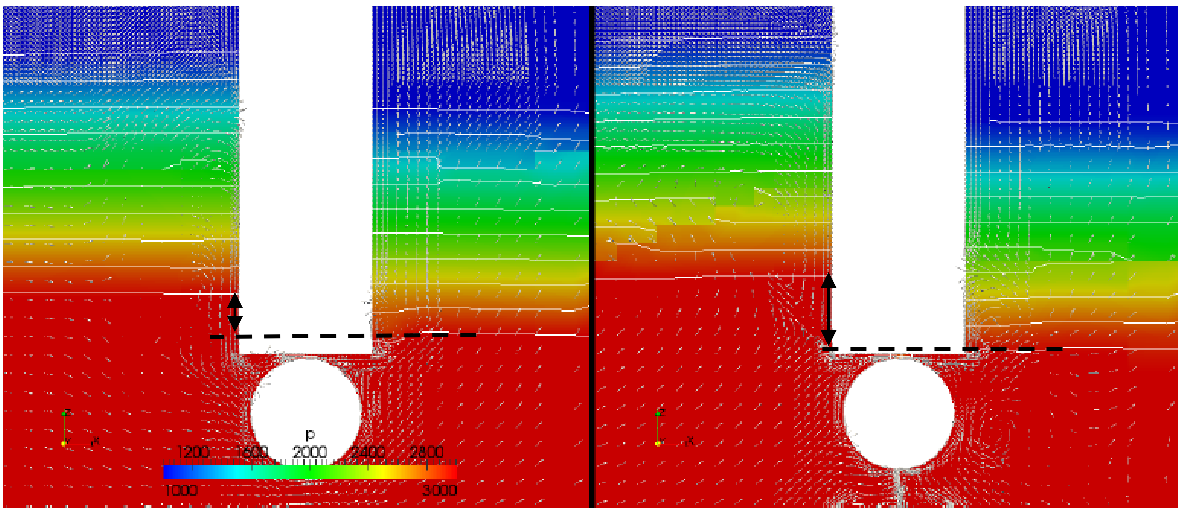


Figure 8. The fluid pressure field surrounding the flap for: (left) a full gap underneath the hinge, (right) a gap block structure present. White contour lines denote pressure isobars and it is evident that there is a smaller pressure difference between the front and back face of the flap when a full gap (left) is present.

- Further evidence of the reduction in wave torque due to the presence of the gap is demonstrated by the CFD results of [A6]. Figure 9 shows a snapshot of the surface elevation level on the front and back face of the flap at the same point in time during a wave cycle when the gap is blocked (black data points on the left) and fully open (red data points on the right). The x-axis denotes the distance from the centre of the flap (i.e. along the flap width) and the data for each gap configuration has been symmetrically mirrored for display purposes.

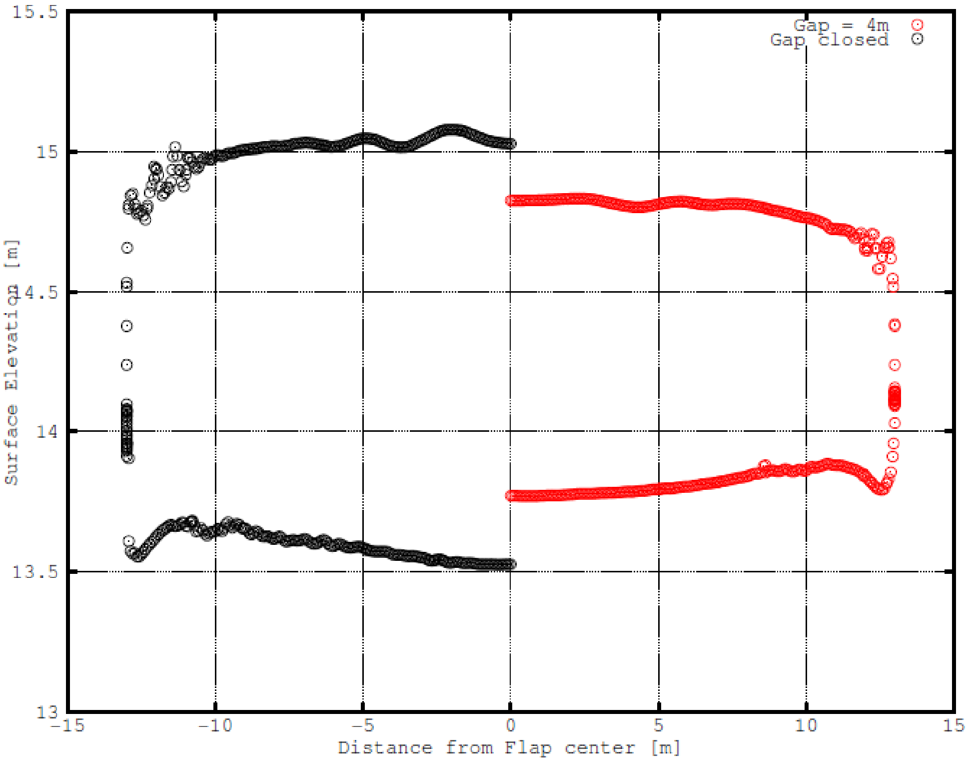


Figure 9. Snapshot of the surface elevation on the front and back face of the device for: (left – black) the gap fully blocked and (right – red) the gap present.

Similar to before, the presence of the gap allows fluid to flow from one side of the flap to the other much easier (underneath the hinge line). This in turn reduces the pressure differential between the front and back face of the flap which then manifests as a smaller surface elevation differential.

- A final illustration that the magnitude of the induced wave torque is linked to the ability of the flap and surrounding structure to impede the fluid flow path is also given by [A6]. A novel structure was developed which consisted of a large horizontal plate located at the hinge level of the device, see Figure 10. Despite the large gap that is still present underneath this horizontal plate, the time trace of the induced wave torque (graph on the right of Figure 10) shows that the horizontal plate increases the wave torque magnitude. This increase (although not as effective as fully blocking the gap) can be attributed to the more difficult flow path the fluid must travel to get around the device, thus increasing the 'diffraction' force element of the incident waves.

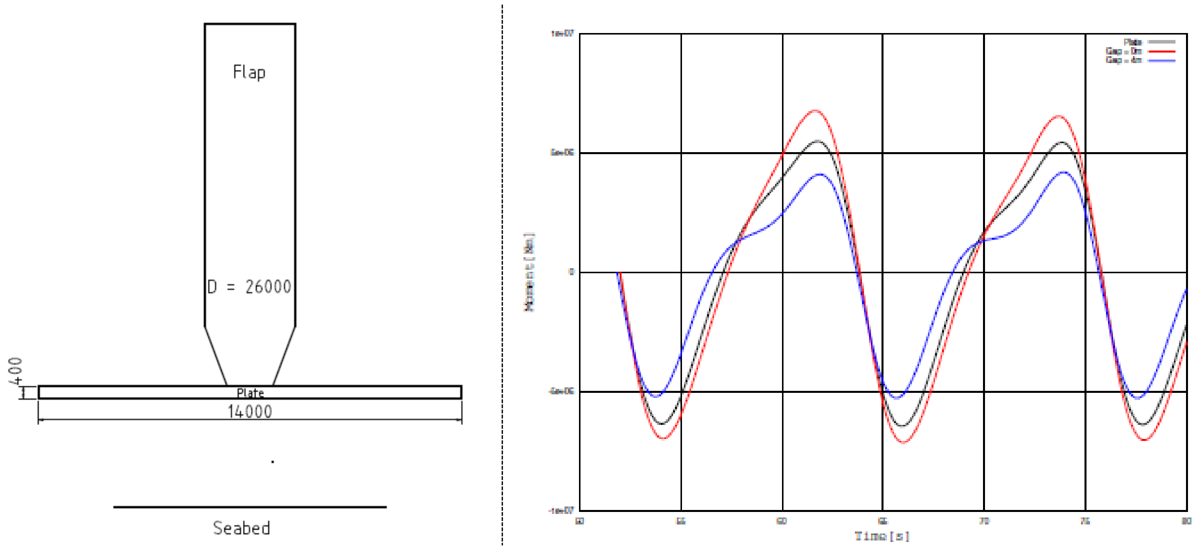


Figure 10. Left: Side elevation of the flap geometry with a large horizontal plate at the hinge level. Right: time-trace of the wave torque (in Nm) induced on the flap for: (red) gap fully blocked with a seabed mounted structure; (black) horizontal plate only; (blue) no bottom structure at all (i.e. gap fully open)

3. **It is more detrimental to have a gap closer to the hinge line (or moving part) of the device rather than the same size gap close to the seabed.**

   Following on from the knowledge that for a pitching flap the wave torque magnitude and power capture are intrinsically linked, [A2] calculated the wave torque for various gap sizes using the BEM code WAMIT. Figure 11 shows that if the gap blocking structure fills the space immediately underneath the hinge line of the device (but leaves a gap at the seabed), the loss in wave torque is less severe than the reverse scenario. This aligns with the explanation that the greater an obstacle the flap can be to the fluid flow path the larger the wave torque, which in turn presents the opportunity for large power capture by the flap.

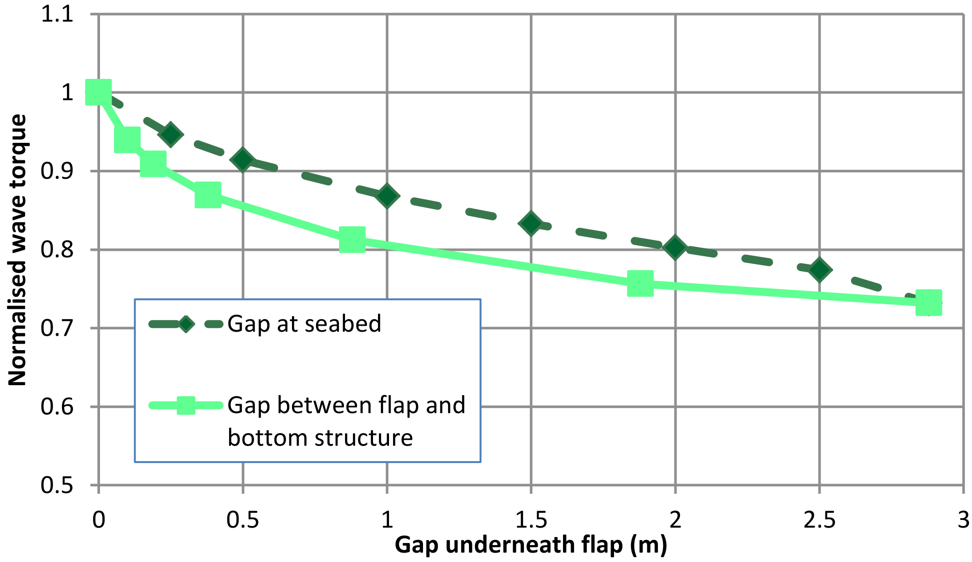


Figure 11. Wave torque induced on the flap for various size gaps present directly underneath the hinge line (solid line) and at the seabed (dashed line). Torque values are normalised by the case when the gap is fully closed.

4. **If a gap blocking structure is built from the seabed up, the precision with which the gap must be closed is very high to mitigate against significant power loss.**

   Figure 12 shows the numerical hydrodynamic simulations conducted by [A4]. Although there is interpolation between data points, it can be seen that even a 0.5m gap underneath the hinge line of the device can result in a circa 10% reduction in the annual average power capture of the flap. The rate at which the power is lost, diminishes as the gap size increases and would appear to plateau above approximately 2m. Similar qualitative characteristics were also seen in Figure 11 for the wave torque induced onto the flap.

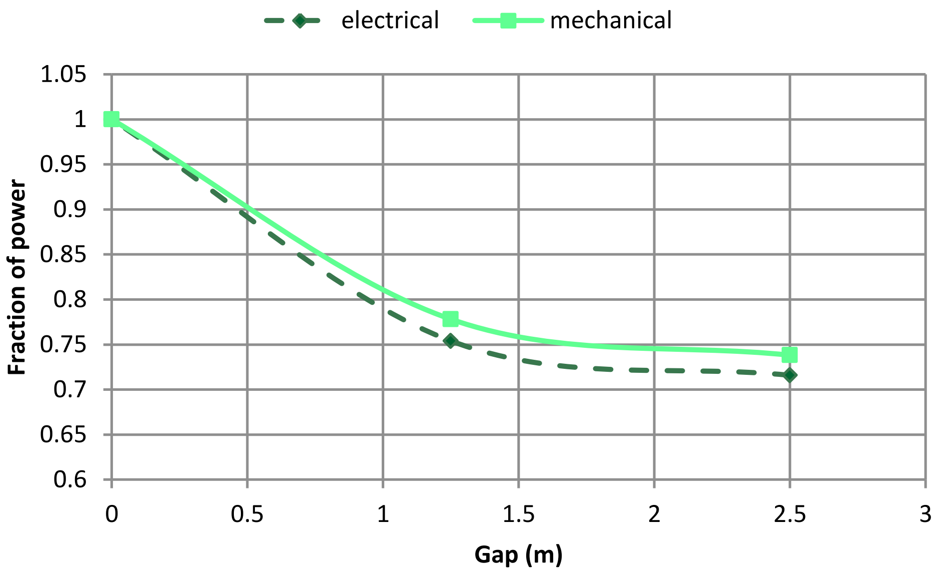


Figure 12. Impact of gap size on the annual energy power capture of the 26m wide Oyster800 flap. (Power values have been normalised against the case when the gap is fully blocked).

   Note: the simulations performed in [A4] used a fully coupled hydrodynamic-hydraulic model of the Oyster800 flap-PTO system. As such the PTO damping was optimised to maximise the electrical power output of the system. Although closely aligned, the setting which optimises the electrical power output of a real hydraulic circuit may not be the optimal conditions to maximise the mechanical power captured by the flap in the ocean waves. Evidence of this is reflected by the slightly different curves presented in Figure 12.

Summary

The suite of research studies discussed verifies the hypothesis that: the more of an obstacle the device is to the incident waves, the larger the excitation wave torque induced on the device, which subsequently creates the opportunity for more power to be captured by the device.

The impact various gap sizes have on the annual energy production of the Oyster device was quantified via extensive irregular sea state testing, using both experimental and numerical techniques.

5.5 Outcome of the Research

Despite the significance a gap under the hinge line has on the power capture of the device, a robust engineering solution to block the gap to the level of precision required is by no means trivial or inexpensive. For the Oyster800 device, a detailed quantification of the impact on performance came too late in the project schedule. A cost-effective solution could have been developed at the original design stage if this justifiable evidence was available. However, after installation of the Oyster800 device in 2011, it was decided that cost was better spent on component and device reliability. Thus, a gap blocking structure was not considered as part of the initial Oyster800 deployment.

During 2013 and 2014 design studies were completed to deliver preliminary concepts for how a gap blocking structure could be retrospectively implemented on Oyster800. APLs priority to demonstrate the base performance of Oyster800 meant that designs were not taken any further at this stage. Developing a gap blocking solution to a detailed design and implementing it would not only have provided significant offshore operational experience but also an opportunity to quantify the power performance impact of closing the gap and full-scale.

The requirement for gap blocking was in the basis of design for the next generation of WEC, namely Oyster801.

5.6 References

[A1]. Henry, A., (2008), "The Hydrodynamics of Small Seabed Mounted Bottom Hinged Wave Energy Converters in Shallow Water", *PhD Thesis, Queen's University Belfast.*

[A2]. Henry, A., (2008), "QUB AH 080415 - Initial study of the effect of gap underneath the flap using WAMIT - Part2.docx", *Internal Report, Queens University Belfast.*

[A3]. McDowell, A., (2010), "101019 Effect of Gap Under Hinge of OY02a on Performance at 25th Scale APL-RD.FDR.04-REP-0064-A2.docx", *Internal Report*, APL.

[A4]. van 't Hoff, J., (2010), "101108 Oyster 2a power calculations with and without gap - APL-RD.FDR.04-REP-0067 - A4.docx", *Internal Report, APL.*

[A5]. Schmitt, P., (2011), "The influence of a gap under a fixed flap", *Internal Report*.

[A6]. Lampe, T., (2012), "Investigation of the Influence of the Gap flow under the Hinge of a Wave Energy Converter on its Performance", *Bachelor Thesis, Hamburg University of Technology.*

6 (B) Influence of Freeboard on Power and Loading

6.1 Research Hypothesis or Motivation

The hydrodynamic principles of a pitching flap indicate that the more of an obstacle the device can be to the incoming waves, the better it can be at absorbing power. A flap which pierces the water surface helps satisfy this by primarily reducing overtopping losses, i.e. the energy lost by the wave spilling over the top edge of the device. The part of the WEC which is above the water surface is called the freeboard. For a given flap design there is an optimal size of freeboard which balances the performance and loading of the device. Determining this optimal size was the motivation behind APL's freeboard research.

Figure 13. Oyster800 installed at EMEC

6.2 Year and Research Activity

- **2008 – Ref. [B1] – Experimental wave tank testing of a 40th scale pitching flap.**

  Experimental wave tank tests were conducted on a 10m wide flap at 40th scale in the wave tank facility at QUB. Two different studies were considered. The first compared two flaps with different size positive freeboards (i.e. they both pierce the still water level), see Figure 14(a). The second compared a flap with a positive freeboard to one with a negative freeboard (i.e. the flap is permanently below the surface of the water), see Figure 14(b).

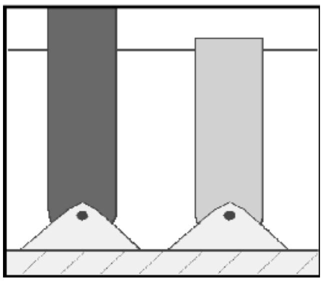
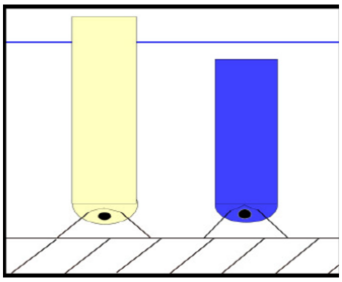
(a)  (b) 

Figure 14. (a) Comparison of two flaps with different positive freeboards. (b) Comparison of a flap with positive freeboard versus negative freeboard.

  Experimental tests were conducted in 6 irregular sea states created with a Bretschneider energy spectrum spanning an incident energy range of 10kW/m to 40kW/m. The PTO damping was optimised in each sea state to achieve the maximum power capture.

- **2009 – Ref. [B2] – Experimental wave tank testing of a 40th scale Oyster 1 device.**

  Experimental wave tank tests were conducted on a 40th scale model of the 18m wide Oyster 1 device at the wave tank facility at QUB. The tests were conducted to gain preliminary insights into the size of freeboard of the next generation Oyster800 machine (referred to as Oyster 2 in the reference). Three different positive freeboard sizes were considered. Each flap configuration was tested in 6 irregular 'performance' sea states to gauge the power capture and 6 'extreme' sea states to estimate the ultimate foundation loads on the device.

2011 – Ref. [B3] – Experimental wave tank testing of a 40th scale Oyster800 device.

Experimental wave tank tests were conducted on a 40th scale model of the 26m wide Oyster800 device at the wave tank facility at QUB. Two flap variables were simultaneously explored in this research as part of a parameter mapping study. These were: the freeboard size; and the flap's buoyancy restoring-torque (referred to as the 'pitch stiffness'). Three different positive freeboard sizes were considered and at least 3 different pitch stiffness levels (see Table 1). Note: pitch stiffness values are expressed as per metre of flap width.

Freeboard (m)	Pitch Stiffness (MNm/rad/m)
1.6	0.5000; 0.8077; 1.1923
2.6	0.5007; 0.8592; 1.1951; 1.6155
3.6	0.6830; 1.1417; 1.5944

Table 1. Full scale freeboard and pitch stiffness (per meter flap width) values of the 26m wide flap during wave tank tests.

Tests were conducted in 7 irregular sea states at a water depth of 13.4m (full scale equivalent). The PTO damping was 'optimised' in every sea state up to a mechanical torque limit of 8MNm, which was reflective of the capacity of the real Oyster800 PTO system. Extrapolation and interpolation algorithms were then used over the 7 'optimal' mechanical power values to get a full device power matrix across a wider H_s – T_m range (significant wave height – mean wave period). This power matrix was then multiplied by an EMEC frequency of occurrence scatter matrix to achieve an annual average mechanical power value.

2012 – Ref. [B4] – Conceptual model of a bottom-hinge flap-type OWSC.

This review paper collated together a range of information about the operating principles of a nearshore OWSC and the technical development of Oyster. The information which is of most relevance here, is an investigation of the wave torque induced on an 18m wide flap of varying freeboard sizes, from positive to negative freeboard. This analysis was conducted using the BEM code WAMIT and a very useful discussion is given on the conceptual operation and interplay between the various driving factors of an OWSC.

2010 – Ref. [B7] – Experimental investigation of novel load reduction designs.

Experimental wave tank tests were conducted at 40th scale on an early design of the Oyster800 device (Figure 15) at the wave tank facility at QUB. This initial tubular flap design experiences high peak loads in storm conditions, particularly in the surge degree of freedom. The focus of the research was to explore novel methods to reduce the peak loading on the structure. Particular emphasis was put on modifying the geometric shape and profile of the flaps top edge/freeboard.

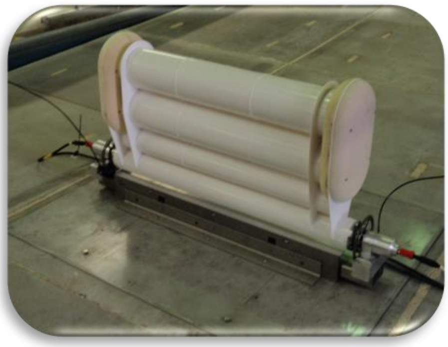


Figure 15. Preliminary design of Oyster800 with large upper tubes

6.3 External Influences on the Research Programme

The key influence on the freeboard research programmes was the commercial timescale of APL in the development of the Oyster800 device. The optimal freeboard size, which balanced both the power capture and loading on the device, was sought at the early level-2 design requirement stage of the project. Commercial timelines did not permit an exhaustive investigation into associated/follow-on research questions stemming from this work. Thus, there is still scope for further research investigations into several aspects of this topic.

6.4 Results and Conclusions

1. **A change in freeboard size and/or shape can have a subtle yet complex influence on other hydrodynamic features governing the dynamic behaviour of a flap-type device.**

   Although the key motivation behind having a surface piercing flap (i.e. positive freeboard) is to reduce wave overtopping losses, modification of the freeboard size and/or shape also affects other key hydrodynamic features governing the flaps motion. Thus, it is challenging to precisely isolate/decouple and quantify the effect of the freeboard from other variables.

   For example, for a surface piercing flap the pitch stiffness (buoyancy restoring force) continually changes due to different levels of submergence, as the flap oscillates back and force and the wave crest/trough propagates past the device (see also Section 9.1 for further details). Thus, depending on the size, geometric shape and material of the freeboard, the pitch stiffness distribution of the flap will vary over a complete rotation/wave cycle, which affects its dynamic response.

   A flap with a different size freeboard will have a different moment of inertia which will affect the motion of the device. In addition to this, the added inertia and centre of pressure of the fluid can also be affected, resulting in different dynamic behaviour of the device.

   Different freeboard shapes (especially non-uniform or asymmetric shapes) can attract more/less wave force as the wave propagates past the flap. This in turn can position the flap at a different location/phase within a wave cycle. Not only can the transient positioning of the flap relative to the wave effect performance, it can have a significant effect on the loading of the device.

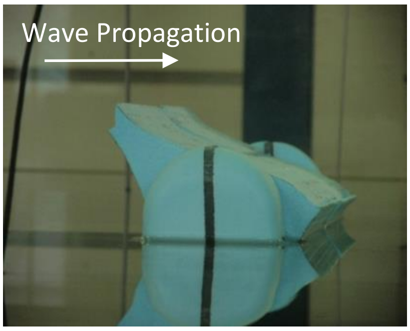


Figure 16. Example of a flap with an asymmetric freeboard shape above the still water line. (Note the reflection of the flap in still water).

   Although these interdependencies were known to APL staff, who made good attempts to decouple the features from each other during their research, there is still scope for further detailed research investigations into the influence the freeboard shape, size and material weight has on the governing behaviour of surface-piercing flap-type devices.

2. **A flap which is surface piercing (positive freeboard) captures ~30% more power than a submerged flap (negative freeboard) with a similar geometry profile.**

Experimental tests conducted by [B1] on a 10m wide flap with a positive freeboard (surface piercing) of 1m and a negative freeboard (not surface piercing) of 0.5m shows a dramatic difference in the power captured. Figure 17 shows the capture factor (or capture width ratio) of both flap configurations over 6 irregular sea states of varying energy characteristics. There are three key reasons for the significant power loss. The first is the continual overtopping losses as the incident wave energy readily spills over the top of the smaller device. The second is associated with an overall smaller wave torque induced onto the smaller flap. The third loss mechanism is linked to turbulent/viscous losses associated with fluid flow over the top wetted edge of the smaller flap.

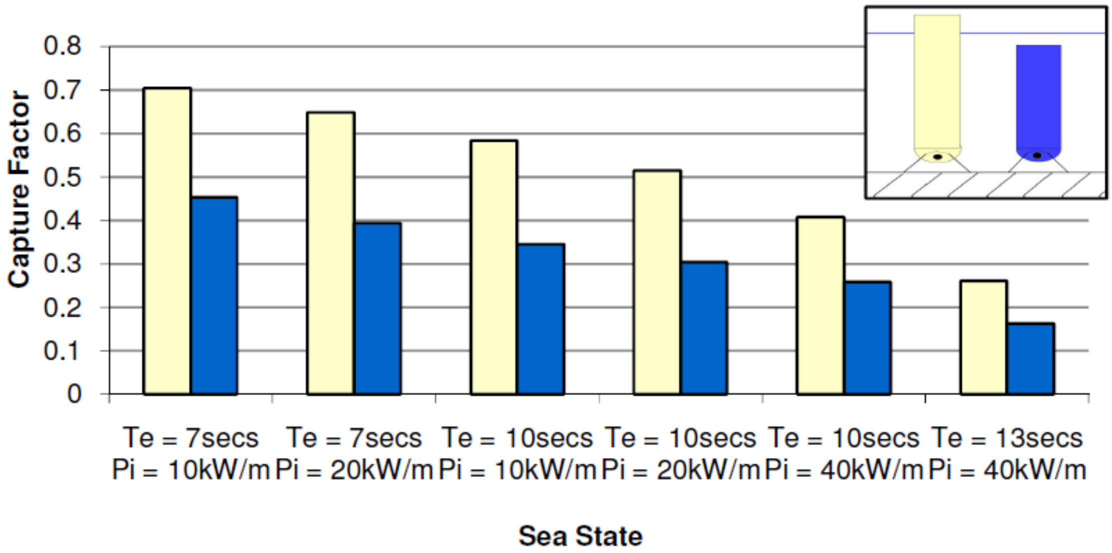


Figure 17. Effect of positive and negative freeboard on the power capture of a 10m wide flap.

The significant reduction in wave torque induced on shorter flaps with negative freeboard has also been presented in [B4]. Given that wave torque is the driving force behind the operation of a flap, this emphasises the impact that piercing the water surface has on the power capture potential of a flap-type WEC.

3. **APL found that within their flap geometry and material design envelope, a freeboard of circa 2.5m was optimal for power capture.**

The bulk of APL’s research focused on wide rectangular flaps, which are surface piercing and located in approximately 13m water depth. [B2] investigated the effect of increasing the freeboard from 1.5m to 3.5m on an 18m wide flap. There was a significant 15% increase in the annual average power capture as the freeboard extended from 1.5m to 2.5m. Very little performance gain was found if the freeboard extended further from 2.5m to 3.5m, as shown in Figure 18.

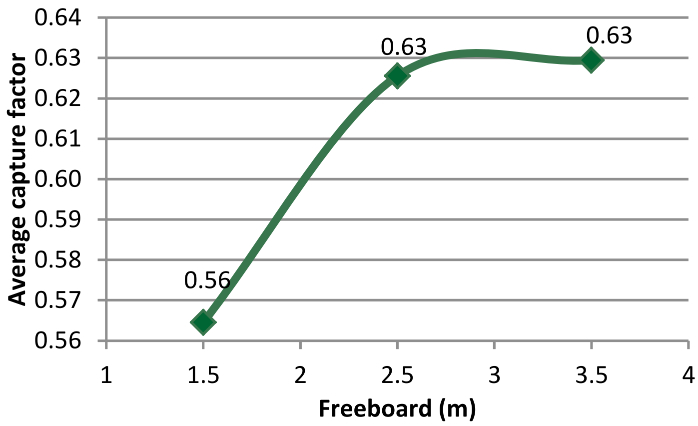


Figure 18. Average annual power capture factor for an 18m wide flap for 3 freeboard sizes.

An extensive set of independent tests were conducted by [B3] on a 26m wide flap. Here a two-variable parameter map of freeboard and pitch stiffness was investigated. For a given pitch stiffness value (within the engineering constraint range of the study), the optimal freeboard size was found to be 2.6m. Again, there was a noteworthy increase in power capture of 19% as the freeboard extended from 1.6m to 2.6m. The annual average power then reduced again as the freeboard increased from 2.6m to 3.6m.

The consistent optimal freeboard size returned from these two independent studies is a reflection of: (a) the wave climate conditions considered by APL (i.e. the 13m depth nearshore site at EMEC), as this size minimises the overtopping losses of the most commonly occurring power-contributing sea states; and (b) the level of pitch stiffness (net buoyancy) achievable with the size and material choice (steel) for the Oyster device.

4. Consideration of tidal level variations is crucial in the optimisation of freeboard size.

Bottom-hinged flap-type devices are typically located in the nearshore region so that they can exploit the enhanced horizontal motion of the waves. This in turn exposes the device to tidal/water depth variations. For a given flap geometry, the tidal range must be considered in the optimisation of the freeboard size. A detail discussion of the effect tidal variations has on the performance of a flap is beyond the scope of this section. However, a detailed summary of the work APL conducted into tidal level effects is given by [B5].

To quantify the impact tidal variations can have on the annual power performance of a device, APL developed a robust time-series methodology to account for the tidal level, see [B6] for details. Results show that for the Oyster800 device, whose freeboard has been optimised at the Mean Water Level (MWL) at the EMEC site, tidal level variations (circa 2.5m range) can reduce the annual average power capture by 4.3%.

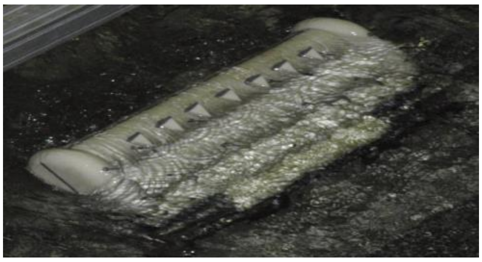
5. **The shape profile of the flaps freeboard/top edge has a significant influence on the peak loading experienced by device.**

An extensive experimental study into the effect the shape of the top edge of the flap has on the peak loads experienced during storm conditions is presented by [B7]. The research was triggered from very large surge loads that were recorded (during experimental testing) on a preliminary tubular design of the 26m wide Oyster800 flap (see Figure 15 or Figure 19(a) for image of the scale model(s) of this concept used in the QUB wave tank). Preliminary analysis discovered that the peak load was induced when the flap was pitched over towards the shore (at the end of its rotation) and the large waves were overtopping the device. Thus, the motivation was to try and find novel top-edge shapes that would reduce this load mechanism.

(a) Oyster800 tubular concept

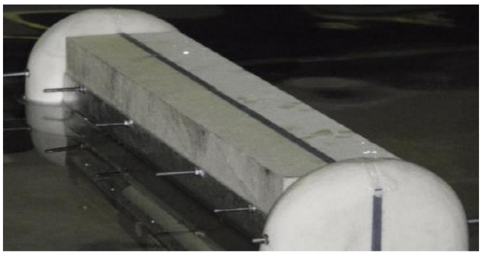
(d) Saw-tooth ‘diffusers’ along top edge

(b) Protruding strips on the front & back edge



(e) Plan-view of the ‘diffuser’ model

(c) Oyster800 concept with a small top tube



(f) Flap with a ‘Full Box Top” edge profile

Figure 19. Example of some of the top-edge flap variations tested to try and reduce the peak surge load

High pitch stiffness (net buoyancy restoring torque) was identified as a key parameter which catalysed the large surge load i.e. more buoyant/stiffer flaps could not ‘get out of the way’ of the storm waves as effectively. However, from a power capture perspective, having a high pitch-stiffness is very advantageous. Thus, the pitch stiffness of each flap variation was closely monitored so that the true effect of the top-edge profile could be isolated.

Figure 20 shows a summary of all flap shape variations which were investigated by APL. The solid blue line is the original Oyster800 flap geometry (see Figure 19(a), which is referred to as "OY02 Original" in the legend of Figure 20) but with different levels of pitch stiffness. This line represents how changing buoyancy alone affects the peak surge load. It can be seen that the top-edge shape can have a significant effect in reducing this loading mechanism. It should be noted that for brevity, Figure 19(a-f) only shows a sample of the key top edge variations tested. Not all the flap shapes plotted and referred to in the legend on Figure 20 are depicted. The reference to a 'Cover Plate' is where a flat plate was attached on the front and back face of the flap over the top two tubes. The motivation was to determine if the tubular profile was contributing to the surge load experienced. Three key conclusions can be drawn from these results:

- Top-edge diffusers (Figure 19(d), (e)) distorts the fluid flow over the top of the device, reducing the drag on the device at the end of its rotation stroke.
- The protruding strips along the top edges (Figure 19(b)) referred to as "Front & Back Strips" in the legend of Figure 20, induces a larger wave torque on the flap. The result of this is that the flap rotates further and stays submerged for longer. This temporarily positions the flap in a different phase of the wave cycle altering the loading on the structure.
- A smaller top tube (Figure 19(c)), referred to as "Small top tube" in the legend of Figure 20, modifies the buoyancy distribution of the flap. This influences the dynamics and relative phasing of the flap motion in the wave. But the tapered profile shape also modifies the fluid flow and drag characteristics. These combined effects significantly reduce the peak surge load as can be seen from Figure 20.

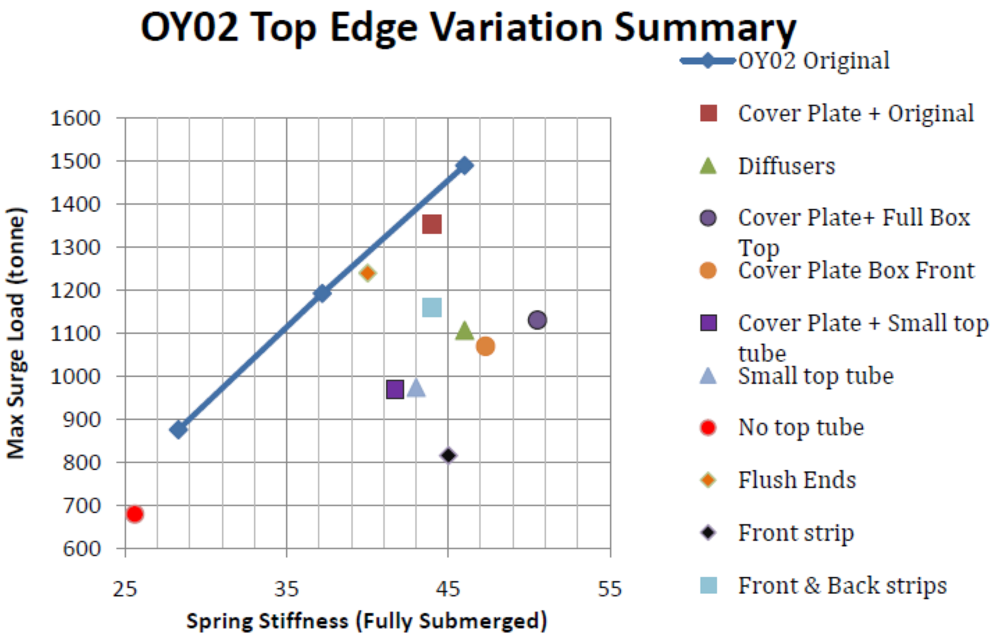


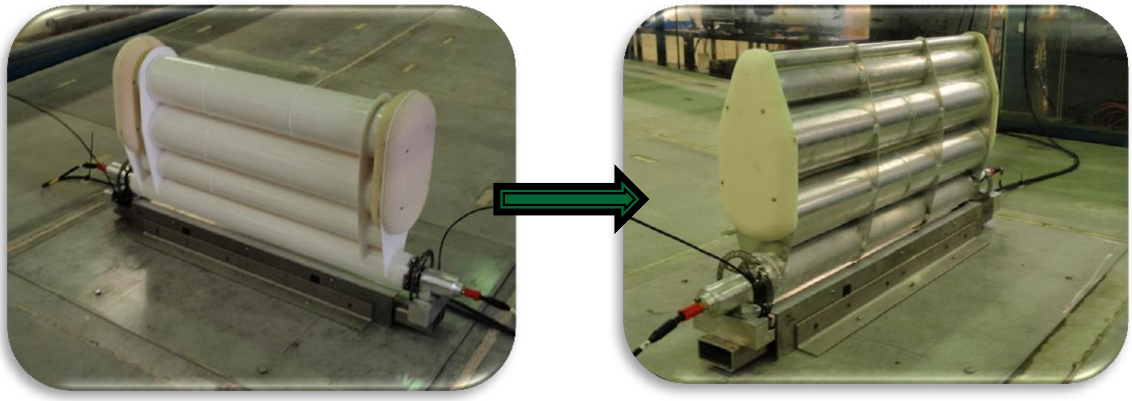
Figure 20. Summary of the peak surge loads recorded for every flap model (top-edge) variation tested. (Note: the pitch stiffness on the x-axis is measured in MNm/rad. All quantities are reported at full scale).

6.5 Outcome of the Research

In addition to the knowledge gained by APL, two significant engineering results stemmed from this research.

The first was the modification of the shape of the tubular Oyster800 flap. Originally, it was proposed that the device was to be constructed from 4 horizontal tubular structures with the two largest diameter tubes at the top of the device (see Figure 21(a)). This design was later modified to have the larger tubes lower down (to maintain adequate levels of pitch stiffness) and smaller tubes tapered towards the top (see Figure 21(b)). This latter design is the Oyster800 device which was built and installed at EMEC in 2011.

The second key result relates to the size of the freeboard for the Oyster800 device. As presented in this section, the research found that a freeboard of 2.6m was the optimal size for the Oyster800 flap. Although there may be some dependency of the optimal freeboard size on flap width, it is more an indirect relationship linked through the devices mass-buoyancy distribution and structural design.



(a) Original tubular Oyster800 concept proposed (b) Final Oyster800 concept installed at EMEC

Figure 21. Modification of the flap profile following on from the freeboard research programme.

6.6 References

[B1]. Henry, A., (2008), "The Hydrodynamics of Small Seabed Mounted Bottom Hinged Wave Energy Converters in Shallow Water", *PhD Thesis, Queen's University Belfast.*

[B2]. Henry, A., (2009), "OY02-DES-REP-INT-2 Effect of freeboard on performance and loading of an 18m flap", *Internal Report, APL*.

[B3]. MacLeod, A., (2011), "110909 Parameter Map Free Board Study - APL-RD.FDR.04-Rep-0101 - A1", *Internal Report, APL*.

[B4]. T. Whittaker and M. Folley, (2012) "Nearshore Oscillating Wave Surge Converters and the Development of Oyster", *Philosophical Transactions of the Royal Society A,* Vol. 370, pp. 345-364.

[B5]. Henry, A., (2011), "110421 A Review of Work to Date on the Effect of Tidal Levels - APL-RD.FDR.04-REP-0089 - A1", *Internal Report, APL*.

[B6]. Lengden, S., (2010), "101011 Influence of Tidal Level Variation on Oyster2a Power - APL-RD.FDR.04-REP-0063 - A1", *Internal Report, APL*.

[B7]. Lynch, P., (2010), "A study of the novel methods to reduce wave loads on flap-type devices", *BEng Project Dissertation, QUB*.

7 (C) Operation of a Flap in Deeper Water

7.1 Research Hypothesis or Motivation

The Oyster device was designed to operate in the nearshore region of circa 13m water depth. This decision was initially based on research studies into the exploitable wave energy resource and characteristics of the nearshore wave climate. APL revisited this decision and conducted some internal research studies which explored the possibilities and consequences of moving the flap into different water depths.

7.2 Year and Research Activity

- **2005 – Ref. [C1] – Numerical modelling of a flap-type WEC at two different water depths.**

  A quasi-linear frequency domain numerical model of a flap type device was developed. The modelled flap was assumed to be: surface-piercing; 12m wide; and extended 10.5m below the water surface. Two different water depth scenarios of 12m and 50m were investigated and the power capture and dynamic characteristics in each case explored.

- **2009 – Ref. [C2] – Experimental wave tank testing of a 40th scale flap in four different water depths.**

  Experimental wave tank tests were conducted on a 40th scale model of an 18m wide, surface-piercing flap at the wave tank facility at QUB. Four different water depths of 10m, 13m, 16m and 20m were considered and the power capture performance of the flap at each water depth determined from 6 irregular sea states. A weighting factor was applied to each sea state so that they represented a site of circa 19kW/m. The PTO damping applied to the flap was optimised in each sea state to maximise the power captured. No loads were recorded during this series of tests.

  For each water depth, three flap configuration scenarios were considered:

  1. The height of the flap structure increases with water depth. The freeboard and hinge height is held constant at 1.5m and 4m respectively. See Figure 22a. Thus, the flap height was 7.5m, 10.5m, 13.5m and 17.5m for the 10m, 13m, 16m and 20m water depths respectively
  2. The freeboard and flap height is held constant at 1.5m and 10.5m respectively. Thus, the distance between the hinge point and the seabed increases with water depth. See Figure 22b. In this case, the gap underneath the hinge point is blocked with a solid ramp structure.
  3. Same configuration as point 2 above only a gap is present underneath the hinge line. See Figure 22c. (Note: although it was known the gap under the hinge line would have a negative effect, for completeness and to aid an engineering decision, this configuration was tested and quantified as a reference point).

  The natural pitching period of the flaps was held constant at approximately 21s for each water depth scenario. By balancing the inertia-buoyancy characteristics of the flap, the effects of the water depth alone could be better isolated and the results in each case more comparable. Finally, it should be noted that in the 10m water depth case there was no gap present underneath the hinge point at all (i.e. configuration 3 not possible) due to physical constraints.

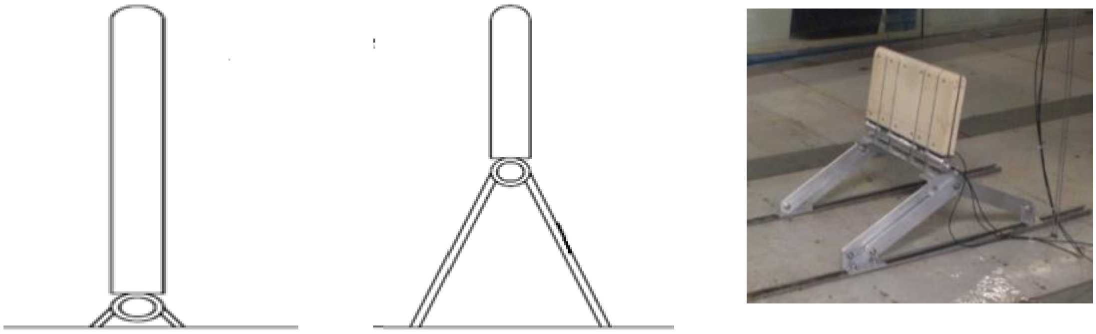


Figure 22. (a) Freeboard and hinge height remain constant at each water depth. (b) Freeboard and flap height remain constant at each water depth. (c) Photo of the 40th scale model with a constant freeboard and elevated hinge height and a gap present under the hinge.

- **2009 – Ref. [C3] – Experimental wave tank testing of a 40th scale flap in 16m water depth.**

Prior to the dimensions of Oyster800 being decided, experimental wave tank tests were conducted on a 40th scale model of a 24m wide flap at 13m and 16m water depth. The power capture performance was assessed in six irregular 'performance' sea states and the ultimate foundation loads were assessed in two 'extreme' sea state tests.

Figure 23. 24m wide flap tested in 16m water depth.

For each water depth, the freeboard and hinge height were held constant at 3m and 4m respectively, i.e. the flap height increased with increasing water depth. A photo of the flap model used during the 16m water depth tests is shown in Figure 23 and shows a rectangular flap with rounded 'end-effectors'.

7.3 External Influences on the Research Programme

APL were proceeding with the development of the Oyster design based on the assumption that 13m water was the preferred water depth. The studies conducted by APL were 'quick' verification tests that there wasn't a more optimal water depth within the practical design envelope. The test results were essentially a "yes – no" justification for moving away from the default assumption of 13m. Thus, if there was no strong evidence to change, then the commercial deadline of APL did not permit any further R&D investigation into the topic.

Interpretation of these water depth results requires knowledge of the effect the freeboard and gap under the hinge point of the flap has on power performance. Thus sections 0 and 6 should be reviewed in conjunction with the results presented in this section.

7.4 Results and Conclusions

1. **Moving a flap-type device (i.e. constant/fixed WEC structure) into deeper water has a detrimental impact on power performance.**

   By simply translating a surface-piercing flap-type device into deeper water, whilst maintaining the same structure, the power capture performance is reduced dramatically. The results of [C1] (see Figure 24) show that the power capture of a 12m wide and 10.5m tall flap that pierces the water surface, is reduced by up to a factor of 2 if it is moved from 12m water depth to 50m water depth.

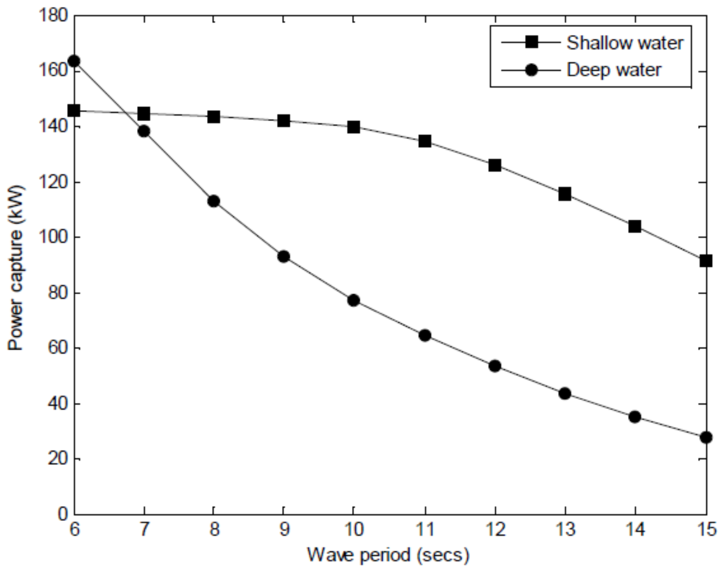


Figure 24. Optimal power capture of a flap operating in: shallow water (12m); and deep water (50m), calculated using a quasi-linear frequency domain numerical model.

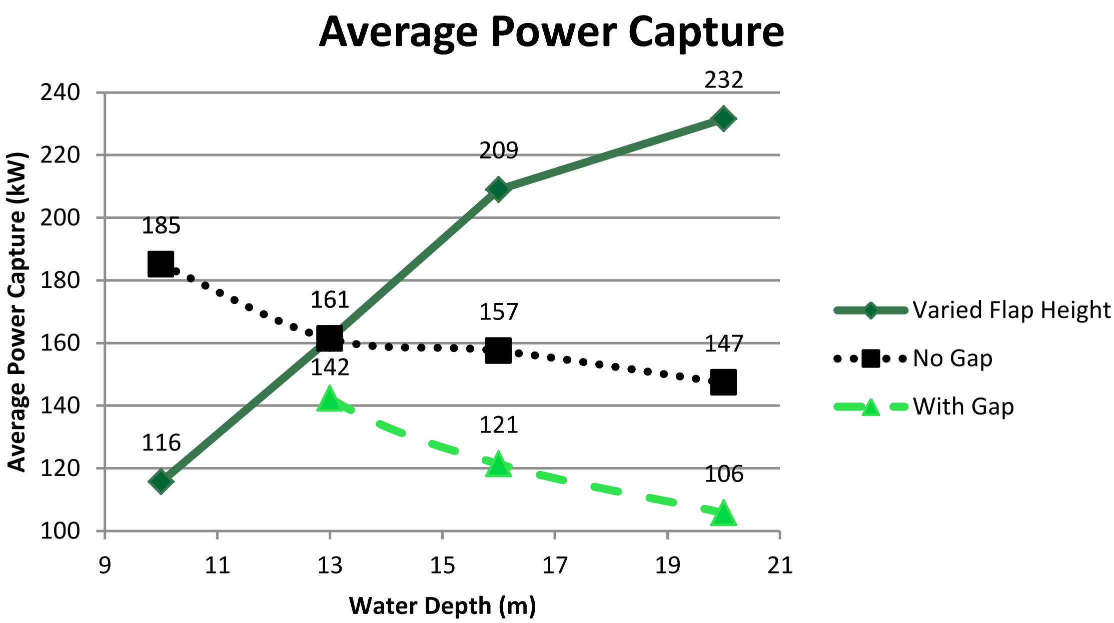


Figure 25. Annual average power capture of three different 18m wide flap configurations at different water depths. (Solid) increasing flap height. (Dotted black) fixed flap structure with the gap under the hinge line blocked. (Dashed green) fixed flap structure with the gap present.

The experimental results reported by [C2] show a similar qualitative behaviour. The dashed green line shown in Figure 25 are the tests results of a 10.5m tall surface piercing flap with a hinge height of 4m, moving from 13m to 20m. (Note: the 10m water depth is not considered here as the hinge height at this depth was reduced to 1.2m). In these tests, the freeboard and flap structure is held constant at 1.5m, but the distance between the hinge line of the flap and the seabed increases with increasing water depth. It can be seen that there is over a ~25% reduction in power captured as the water depth is increased from 13m to 20m.

There are two primary reasons for this significant difference. The first is that the surge wave force of the incident waves, which is associated with the horizontal water particle motion, is amplified in shallow water due to wave shoaling. The second is due to the blockage ratio of the water column. As seen previous in section 0, having a gap underneath the hinge line of the device is very detrimental to the power capture of a flap-type device.

2. **The loading on a deep-water flap, who's structural size increases linearly with water depth, increases more than the additional power captured.**

The experimental results of [C2], given in Figure 25, show that if the freeboard and hinge height are held constant as the flap moves into deeper water (i.e. the flap structure itself increases), then there is a noteworthy increase in power capture. However, in order to achieve this power increase, the loading on the flap and PTO system increases more rapidly.

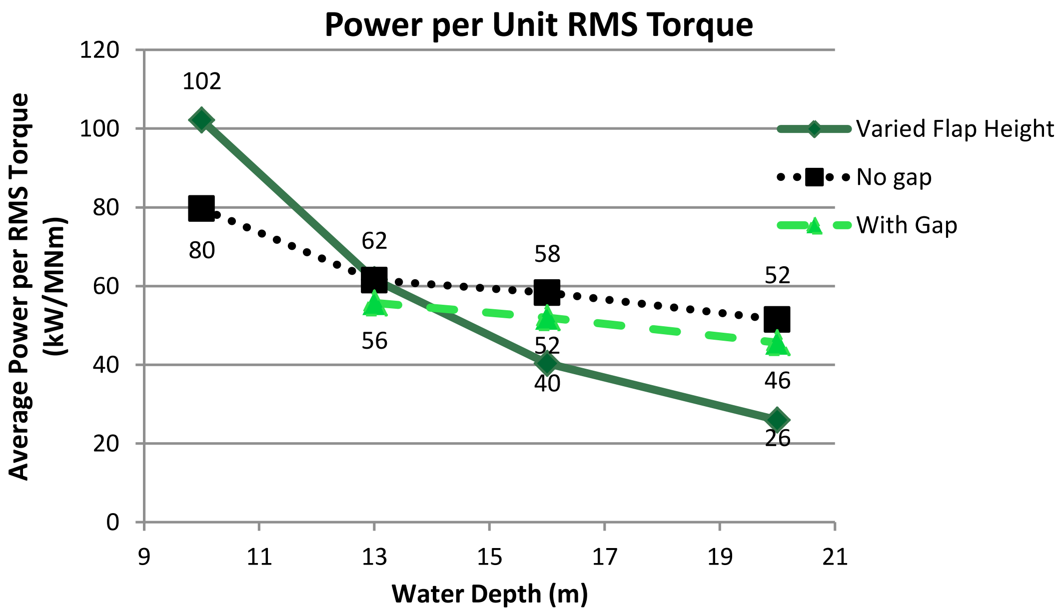


Figure 26. Power capture per unit PTO damping torque induced on each 18m wide flap configuration.

Figure 26 shows the power captured (kW) per unit (MNm) PTO damping torque applied to flap. It is clear that as the flap gets taller, the capacity of the PTO system increases a lot quicker than the additional power the device will capture. In particular, for these tests (i.e. an 18m wide flap) the PTO damping torque range required to optimise the power capture across all sea states tested was within 0.5 – 2MNm at the 10m depth contour whereas a 7 – 17MNm capacity system is required at the 20m depth contour.

A similar result was found from the independent experimental tests of [C3], where it was reported that the PTO damping torque increased significantly for only a marginal increase in power capture for a flap design for a 13m and 16m depth contour. In addition, the heave and surge foundation loads also increased.

It is worth noting that in [C3], the increase in power from 13m to 16m was only 3% whereas the increase in [C2] (see Figure 25) is ~23%. The flap examined in [C3] is a 24m wide, highly buoyant flap with a 3m freeboard and large rounded 'end-effectors' (see Figure 23). Whereas in [C2] it is an 18m wide, lower buoyancy flap with a 1.5m freeboard and sharp rectangular edges. The 24m wide flap has many more optimal features than its 18m wide counterpart. Thus, it is postulated that performance gains introduced by increasing the water depth (and height of the structure) may not be as significant for an already optimised/efficient flap geometry than for a sub-optimal geometry. This statement is however only conjecture and should be a source of further research and investigation.

3. **The rotational range of a deep-water flap decreases as the water depth increases.**

   This result has been demonstrated both experimentally by [C2] and numerically by [C1], where the rotation results have been reported at the point of optimal power capture.

   [C2] reports the Root Mean Square (RMS) rotation range of a flap which increases in size with water depth. The RMS range reduces from 7^{o}-22^{o} at the 10m depth contour to 1^{o}-6^{o} at the 20m depth contour across all 6 irregular sea states tested. This result aligns with the fact that the PTO damping torque increases with water depth at maximum power capture point. This larger torque requirement is generally not desired from a practical design perspective.
   The flap structure considered in [C1] is for a flap of fixed structural size but which is tested in 10m and 50m water depth. Again, the range of rotation is larger in shallow water, for wave period between 7s and 15s. This increase is attributed to the amplification of the horizontal water particle motion and associated surge wave force in shallow water.

7.5 Outcome of the Research

The increase in power capture with water depth initially triggered some consideration of moving the Oyster concept from the default 13m water depth. However, it was quickly concluded that the engineering challenge associated with a significant increase in PTO rating (required to achieve the increased power) was prohibitive. Thus, no further action was taken by APL based on these results.

Although not the primary focus of the research, experimental results at the 10m depth contour did show the benefit of keeping the hinge line of the device as low as possible. However, when considering real bathymetry, such as the rocky sea bed at EMEC, it was felt that a hinge height of <4m was not viable for a practical engineering solution. In addition, moving into the 10m depth contour also introduced other challenges when tidal range is considered. This contour also represents the transition point where significant wave breaking occurs.

7.6 References

[C1]. Folley, M., Whittaker, T., Henry, A., (2005), "The Performance of a Wave Energy Converter in Shallow Water", *6th EWTEC, Glasgow, UK.*

[C2]. Doherty, K., (2009), "OY02-DES-REP-INT-24 The Effect of Water Depth on the Performance of Oyster*", Internal Report, APL*.

[C3]. Henry, A., (2009), "091113 Experimental Results for Oyster 2 in 16m Water Depth A1 APL-RD.FDR.04-REP-0014", *Internal Report, APL*.

8 (D) Impact of End-Effectors on Power Performance

8.1 Research Hypothesis or Motivation

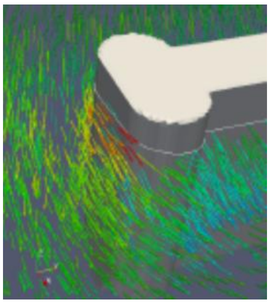


Figure 27. Flow field around the edge of a flap

As with all wave energy converters, the device shape can influence the near-field flow conditions, which in turn can affect the dynamics and performance of the device. As introduced in section 0, high performing flap-type devices are predominantly wave force driven and are posed as a considerable obstacle to the incoming waves. Thus, by design, such a device will significantly distort the fluid flow field, which in turn can introduce parasitic energy effects such as turbulence and vortex shedding. For a bluff body such as a large flap-type device, the side edges of the flap are key areas where such complex flow structures are created. In a flow field, thin and sharp structural edges are known to be active vortex nucleation points. Heuristically, it is generally advised that flaps with square and/or sharp edges should be avoided. However, in terms of a flap-type WEC operating in free-surface waves, a comprehensive explanation of the multifaceted processes involved has been historically lacking. In addition, from a practical engineering perspective, the cost of fabricating large complex flap structural shapes can be prohibitive. Thus, a detailed quantification of the impact the near-body flow field has on the device's power performance is essential to justify any engineering decision.

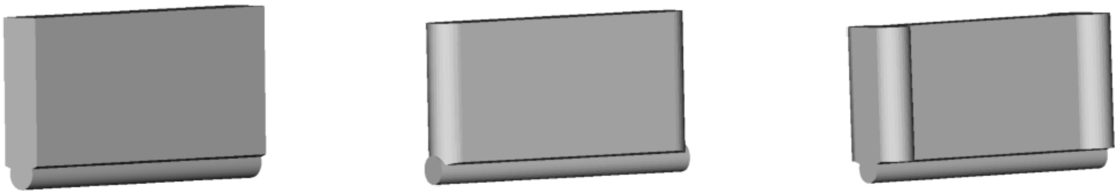
For APL, there were two key motivations for investigating the edge design of a flap-type device. The first was to isolate and ascertain which physical mechanisms involved in the process are either beneficial or detrimental to the power capture performance of the device. Clear insights and knowledge of these mechanisms may lead to different and novel ways to exploit them from an engineering perspective. Secondly, quantification of the overall impact on the devices power capture performance was required to commercially justify any design decisions made in the development of the Oyster WEC.

8.2 Year and Research Activity

- **2014 – Ref. [D1] – Investigation of flap edge-shape on power capture performance using 3D CFD simulations (OpenFOAM) and 40th scale experimental wave tank tests.**

  Under the supervision of QUB and APL, this six month TUHH bachelor thesis project investigated the detailed flow field around a flap-type device with three different end profile shapes. The motivation was to definitively ascertain and quantify what effect the edge shape alone had on power capture performance of a flap. This seminal body of work was one of the last investigations triggered by APL on this topic and built on a large volume of preceding knowledge and information. Thus, this thesis also provides an excellent literature review of the topic at hand and the reader is encouraged to review this document for more in-depth details.

  Advanced Computational Fluid Dynamic (CFD) simulations (using OpenFOAM) and high-quality experimental wave tank tests (at 40th scale) were conducted at the research facility in QUB. Figure 28 shows the three different edge shaped flaps considered in this study. The top row shows a rendering of the flap geometry used in the CFD simulations and the bottom row is a plan view image of the 40th scale wave tank models. The flap dimensions (full scale equivalent) are indicative of the Oyster800 device, i.e. 26m wide, 3.5m thick, 3m freeboard, 9.4m hinge depth from the free surface, operating in 13.4m water depth.



(a) (b) (c)

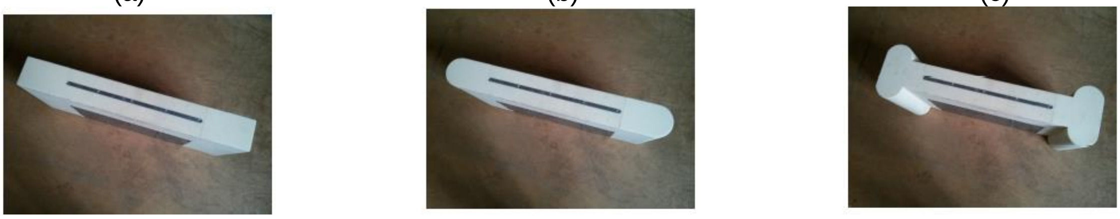


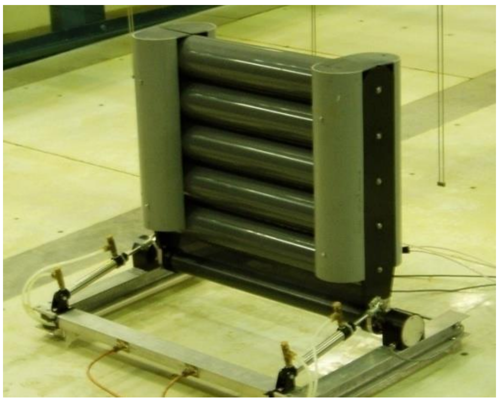
Figure 28. Three flap models with different edge shapes, use in CFD simulations (top) and 40th scale wave tank tests (bottom). (a) Square edges. (b) Rounded edges. (c) Additional half-tubes ("dogbone" flap)

In both the CFD simulations and experimental tests, monochromatic waves were used to gain detailed insights into the near-body flow field around each flap configuration and qualitatively explain the governing principles at play throughout a wave cycle. Three fully spectral irregular sea states were then used in the experimental tests to quantify the impact the edge shape has on power performance.

- **2008 – Ref. [D2] – Experimental wave tank tests of a 40th and 20th scale flap with rounded end-effectors.**

Experimental wave tank tests were conducted on a 40th and 20th scale model of a 10m and 12m wide, surface-piercing flap in the wave tank facility at QUB respectively. The flaps were configured with large rounded end-profiles of circa 4m in diameter (full scale), see Figure 29.

(a)



(b)

Figure 29. (a) 10m wide 40th scale flap, (b) 12m wide 20th scale flap, each with ~4m rounded end-profiles

The 40th scale flap was tested in 6 irregular sea states and the 20th scale model tested in 16 irregular sea states. In each case, the seas were created with a Bretschneider energy spectrum and the PTO damping was optimised in each sea state to achieve maximum power capture. A frequency of occurrence weighting is given to each sea state and an annual average power value determined for each flap configuration.

The performance of the flaps with large rounded end profiles were compared directly to an equivalent width rectangular flap (i.e. a flap with the end profile removed).

2009 – Ref. [D3] – Experimental wave tank testing of an 18m wide 40th scale flap with different end-profile shapes.

Experimental wave tank tests were conducted on a 40th scale model of an 18m wide, surface-piercing flap at the wave tank facility at QUB. Three different end profile shapes were considered and compared to the default rectangular shape flap. The three flap shapes presented in the report are labelled: (a) H-section; (b) Square dogbone; (c) Rounded dogbone; and a plan-view schematic of each flap shape is shown in Figure 30. (Note: the nickname “dogbone” was adopted given the shape of the flap when view from above).

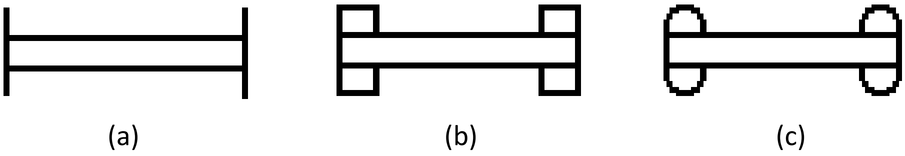


Figure 30. Three flap shapes investigated. (a) H-section, (b) Square dogbone, (c) Rounded dogbone.

Each flap configuration was tested in 6 irregular ‘performance’ seas each created with a Bretschneider energy spectrum. The PTO damping was optimised in each sea state to achieve maximum power capture. A frequency of occurrence weighting is given to each sea state and an annual average power value determined for each flap configuration.

Each flap was also tested in 6 ‘extreme’ sea states to estimate the ultimate loading on the foundation of the device. In these tests, a single nominal PTO damping magnitude was applied to the device.

2009 – Ref. [D4] – Experimental wave tank testing of a rectangular 40th scale flap with independent vertical piles/columns located at the device edges.

A series of 40th scale wave tank tests were conducted at QUB on a 18m wide flap with independent vertical piles/columns located just in front and outside the side edges of the flap, see Figure 31. The piles were surface piercing and extended down to the seabed. Two different lateral spacings of the piles (from the edge of the flap) were considered, which were 0.1m and 2m. In each case, 6 irregular ‘performance’ seas were tested and the PTO damping was optimised in each sea state to achieve maximum power capture. A frequency of occurrence weighting is given to each sea state and an annual average power value determined for each flap configuration. Results were compared to the case when no vertical piles/columns were present.

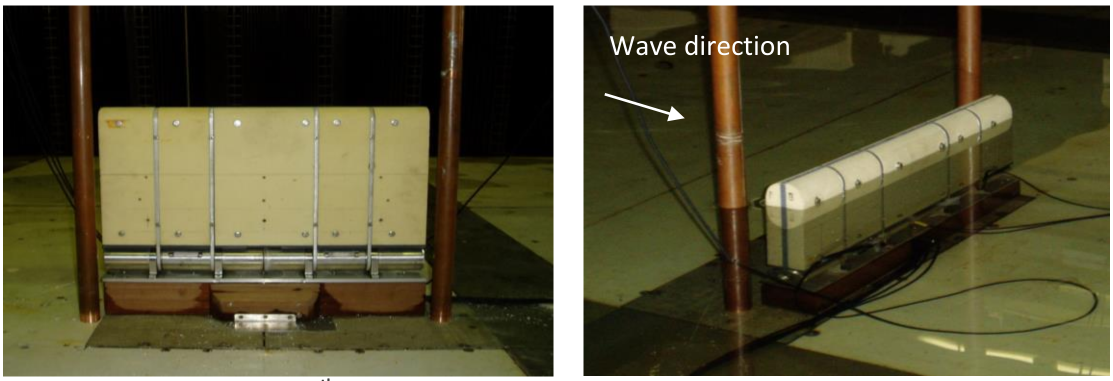
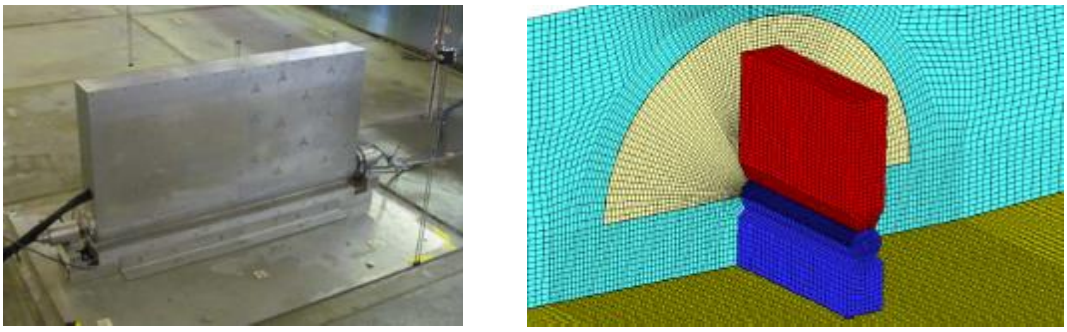


Figure 31. An 18m wide 40th scale flap with vertical piles located 0.1m (full scale) from its edge

- **2015 – Ref. [D5] – Investigation of the fluid structures created around a flap using 3D CFD simulations (ANSYS FLUENT) and 25th scale experimental wave tank tests.**

Researchers from UCD performed advanced 3D CFD simulations (using the commercial code ANSYS FLUENT) on a rectangular surface-piercing flap. They key focus of the study was to examine the viscous flow structures created around the device when operating and to determine the effect these have on device dynamics. The CFD model was validated with high-quality experimental tests performed on a 25th scale flap at the wave tank facility at QUB. Figure 32 (a) shows a photo of the 25th scale model used during the wave tank tests in QUB and (b) the meshed geometry of the flap used in the CFD simulations.



(a) (b)

Figure 32. (a) 25th scale experimental flap model, (b) Meshed flap geometry used in CFD simulations

The global dimensions of the flap model are representative of the Oyster800 device. The equivalent full scale dimensions are: a flap width of 26m, thickness of 3m and height of 12m, operating in a water depth of 13.4m with a freeboard of 2.6m and a hinge depth of 9.4m. Nonlinear monochromatic waves with heights ranging from 1m to 5m (full scale) and wave periods of 10s – 12.5s were used during the study.

Although beyond the scope of this section, this paper also provides interesting insights and discussions into the interaction between the choice of scale (associated with small scale experimental wave tank tests), WEC size and the relative trade-off between competing hydrodynamic forces. Thus, the reader is encouraged to review this manuscript for more in-depth details on these topics.

- **2010 – Ref. [D6] – Assessing the impact of removing the end-effectors on the power performance of the Oyster800 device.**

Experimental tests were conducted on a 25th scale model of the Oyster800 device in the wave tank facility at QUB. The speculative study quantified the impact on power capture of the Oyster800 device if the end-effectors were removed. The flap was tested in 15 irregular sea states, which represent the wave climate at the nearshore site at EMEC and the annual average power capture determined. In order to isolate the pure influence of the end effectors, quantifiable attempts were made to account for the fact that both the flap width and buoyancy are also altered by removing the end effectors, simultaneously affecting the power capture. Figure 34 shows photos of the 25th scale model used during the tests with and without end-effectors.

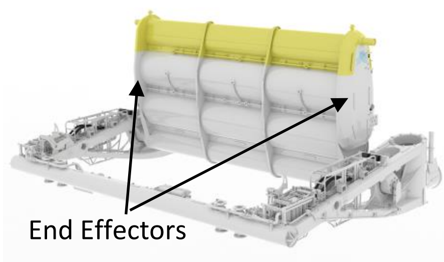


Figure 33. The Oyster800 device

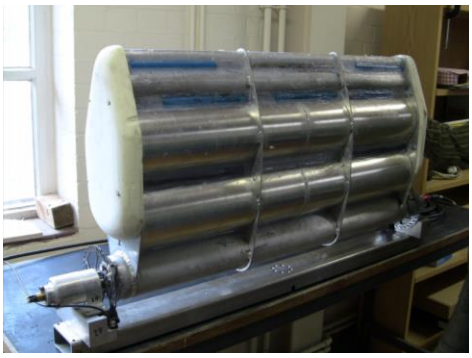
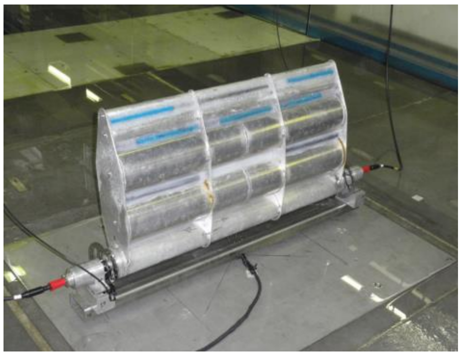
 

Figure 34. 25th scale model of the Oyster800 device with (left) and without (right) end-effectors

- **2013 – Ref. [D7] – Investigation of the near flow field conditions around a flap-type device using 3D CFD simulations (OpenFOAM) and experimental tests.**

  A pioneering Computational Fluid Dynamic (CFD) model (using OpenFOAM) of a surface piercing flap type device was first developed and validated by this QUB PhD project. Multiple features of the flow field surrounding a moving flap and its subsequent influence on the device dynamics, were investigated. The relevant investigations here include: edge shape profile; vortex creation; turbulence; and scaling issues in experimental wave tank tests.

8.3 External Influences on the Research Programme

In the early concept design phase of the Oyster800 device (~2009), there were significant commercial deadlines and schedule restrictions put on the R&D programme, as a concept design for the WEC needed to be defined. Key parameters such as the high-level flap dimensions, operating water depth, decision to include/exclude end-effectors, the associated annual power capture predictions etc. all needed to be specified. Quantitative wave tank tests were conducted to satisfy many of the commercial demands. However, the schedule constraints did not permit a comprehensive R&D exploration to ascertain the fundamental principles and mechanisms behind the edge profile design. These insights were gained in later research efforts but did not directly influence the design of the Oyster800 device.

8.4 Results and Conclusions

1. **Vortex and turbulent structures are created at the edge of a rectangular flap as it oscillated back in forth in waves, which have a negative effect on power capture.**

   The creation of vortex and turbulent structures at the edge of a flap-type device has been repeatedly observed by APL staff during years of experimental wave tank testing. Thus, empirical evidence of their presence is undisputed.

   Both [D5] and [D7] present excellent images of these flow structures and turbulence characteristics that are created at the edge of a 26m wide rectangular flap. Figure 35 gives a good example of the type of vortex structure that is created at the edge of the flap, observed in both CFD simulations and experimental tests. The vortex is created by high flow velocity that whips around the edge of the flap

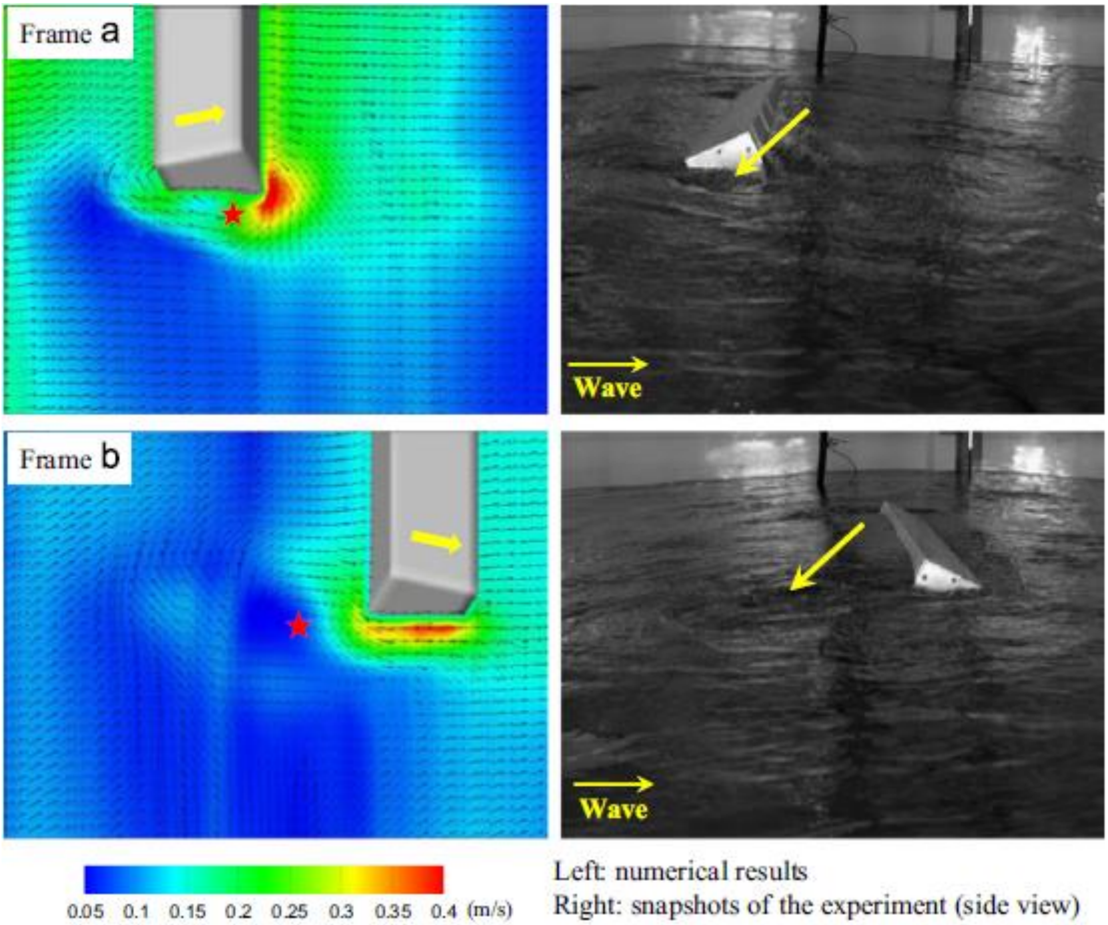


Figure 35. Vortex structure being shed from the edge of a 26m wide rectangular flap. Predicted by CFD simulations (left) and observed in 25th scale experimental wave tank tests (right). The red star and yellow arrow denote the centre of the vortex. The colour scale in the CFD results indicates flow velocity magnitude.

Figure 36 shows the plan-view image of the flap during a wave cycle. High vorticity is created at the edge of the flap by large relative flow velocities between the flap and the surrounding fluid. It can be seen that the life-cycle of a given vortex (i.e. with either positive or negative vorticity) is short lived and dissipates mostly within a half-period cycle. (Note however, the dissipation will not be quite as rapid at full scale, see [D5] and [D7] for more details).

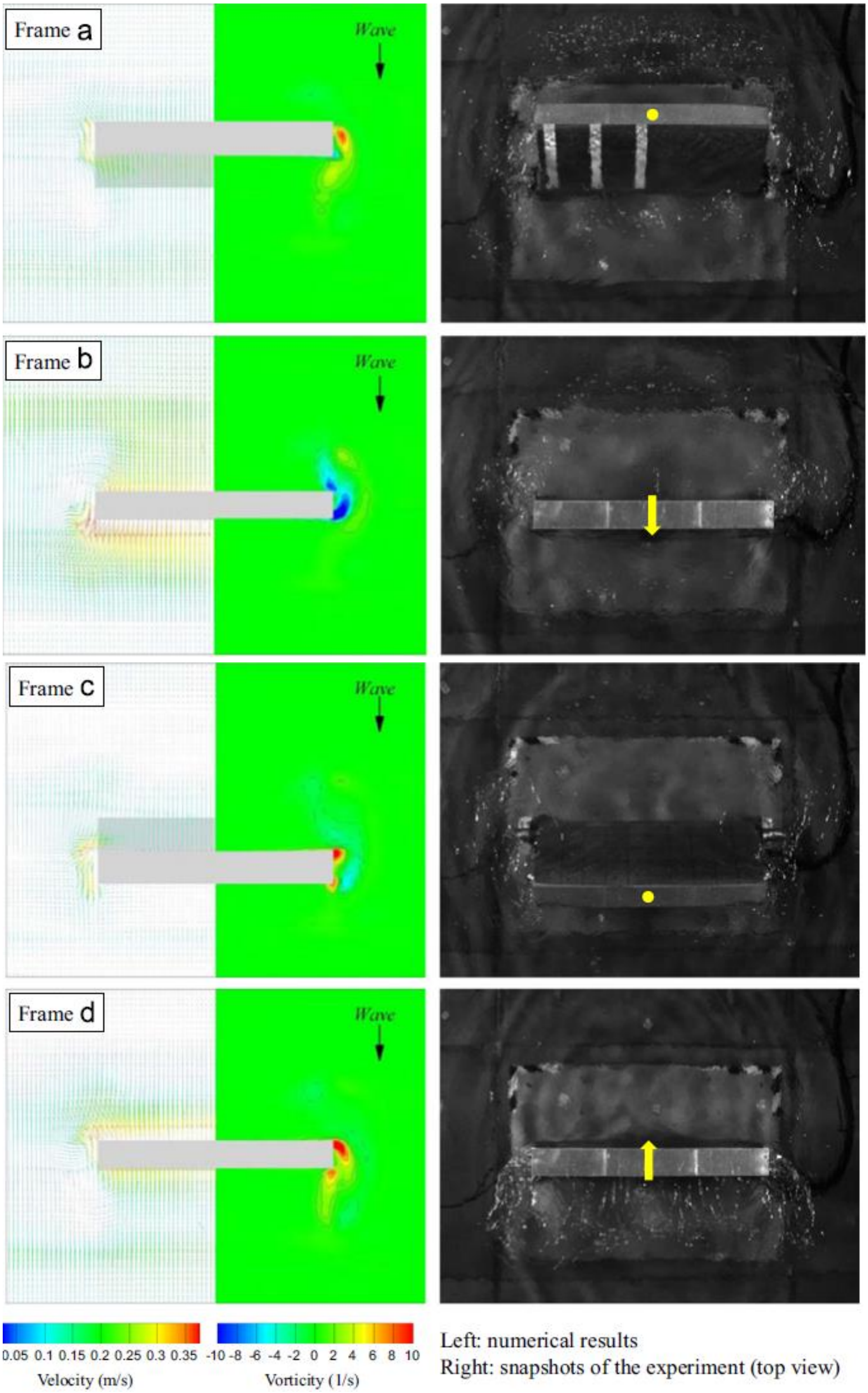


Figure 36. Flow velocity and vorticity fields (left) around the 26m wide flap during a wave cycle. (right) the plan view images of the 25th scale experimental tests.

It is interesting to note from Figure 35 and Figure 36 that the characteristic dimension of the vortices is of the same order as the flap thickness, circa 3m-4m in this case. This is much smaller than the characteristic dimension of the flap itself, which is 26m. The vortices are created locally at the edge of device. This eludes to the fact that for wide flaps, the vortex structures may be less influential than on a narrower flap. However, further research should be conducted to directly verify this hypothesis.

At different points throughout a wave cycle, the buoyant flap will travel faster than the surrounding fluid. In these instances, the flap imparts energy to the fluid (which is then dissipated as turbulence and vortices) which could otherwise have been absorbed by the WEC's PTO system. Thus, vortex structures generated at the edge of the device are evidence that energy is being lost by the WEC. Further evidence of this was obtained from the 40th scale experimental tests conducted by [D4]. As presented in section 8.2, two vertical piles were positioned in close proximity (0.1m), but independent to the edges of an 18m wide (full scale) flap. It was observed during the tests that the vortices were created and detached from the vertical piles, rather than the flap itself. As a consequence, the average power capture was recorded to increase by circa 10%. This performance increase diminished to circa 8% as the latter spacing increased to 2m from the edge of the device. Nevertheless, this demonstrates the energy loss magnitude of the parasitic vortex structures.

The turbulent kinetic energy in the fluid surrounding a flap was investigated by [D1] and [D7] using advanced CFD simulations. Figure 38a shows the distribution of turbulent energy in the fluid around a rectangular flap over a half-period of its oscillatory cycle. What is interesting to note is the extent with which the turbulence extends down towards the hinge line. This shows that the sharp edges of the rectangular flap distort the flow well below the surface, thus owing to a loss in energy capture. A consequence of this turbulence manifests as a distortion of the water surface around the edge of the flap, where the flow velocity and turbulence is greatest. This was regularly observed during experimental wave tank tests and Figure 37 shows an example of this irregular distortion taken from the CFD simulations results of [D1]. Local drops in surface elevation coincide with areas of high turbulence intensity.

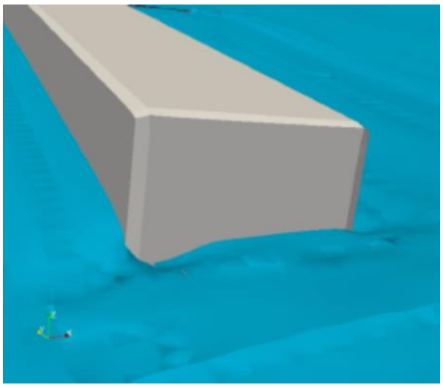
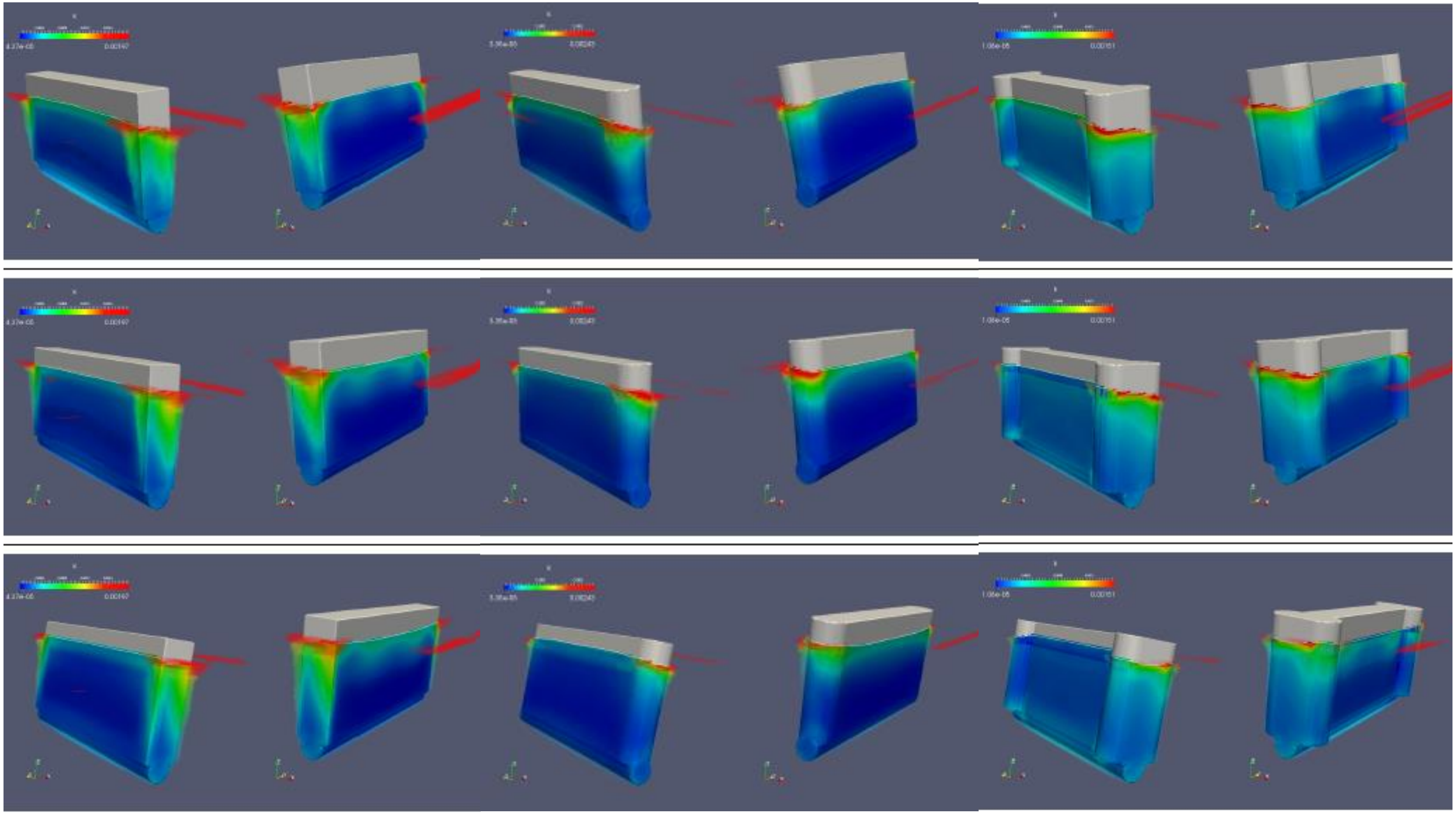


Figure 37. Distortion of the water surface around the edge of a rectangular flap



(a) Rectangular Flap (b) Rounded Edges (c) End-Effectors ("dogbone")

Figure 38. Turbulent kinetic energy around three different flap shapes during a half-period wave cycle. (left) seaward face, (right) landward face of the device.

2. **Rounding the edges of a flap reduces the turbulent kinetic energy of the fluid at the edges of a wide flap and can create an overall power performance increase of circa 5%.**

   The effect rounding the edges of a flap has on power capture performance was investigated in detail by [D7] and [D1]. CFD simulations were performed in irregular wave conditions by [D7] who found that the power capture increased by circa 5% (relative to an equivalent width rectangular flap) due to a reduction in the turbulent kinetic energy induced in the surrounding fluid. The reduction in turbulent kinetic energy is very apparent when comparing Figure 38(a) and (b). The extent with which the turbulence extends below the surface towards the hinge is reduced significantly. Evident of this is also given in Figure 39(a) and (b) which shows a much more streamlined and lower velocity flow around the edge of the rounded flap. Thus, minimising the turbulence generated. (It should be noted that the colour scale for the velocity plot in Figure 39(a) is larger than Figure 39(b). Thus, the disparity in velocity is greater than what might initially be concluded on first inspection)

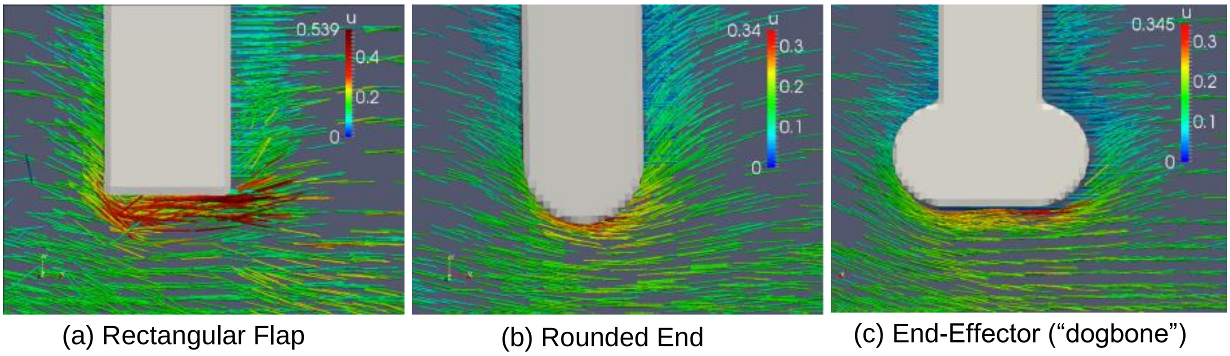


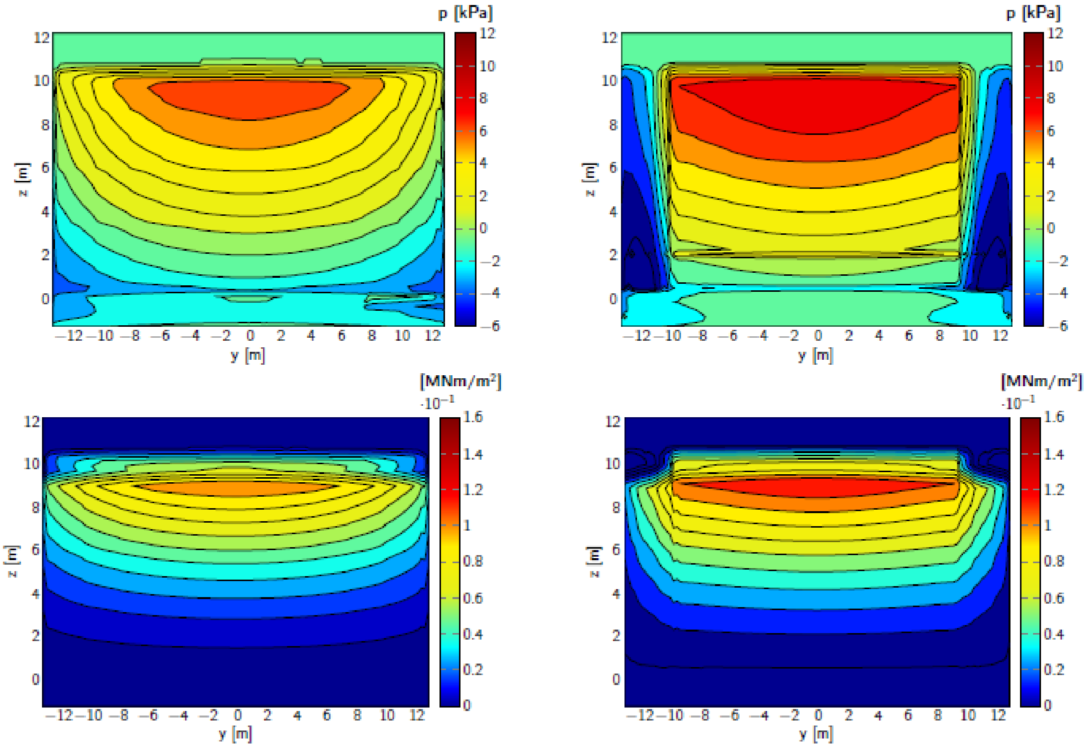
Figure 39. Flow velocities around a flap with three different edge profiles at the point of maximum wave torque. Note the larger magnitude velocity colour scale on (a) the rectangular flap results.

Similarly, 40th scale experimental tests reported by [D1] show on average a 5% increase in power capture in irregular sea states by simply rounding the side-edge profile of the flap. However, the performance gain did reduce as the significant wave height of the seas increased from 1.25m up to 2.75m, as other more complex flow phenomena and turbulence mechanisms (such as wave overtopping) start to play a role.

3. **A flap with large rounded, protruding end-effectors increases the power capture of the flap via two different, but coupled, mechanisms: (1) reduction of turbulent flow; (2) increasing wave torque due to ‘flow entrapment’ by the edge shape.**

   Attaching large rounded end-effectors to the edge of a flap (dogbone shape flap) can affect the flow pattern and thus the dynamics and power capture of the flap in two ways. The first is a reduction of turbulent loss around the edge. The second is an increase in wave torque induced onto the flap due to so-called ‘flow entrapment’ by the protruding ends. Despite being two different mechanisms, the cause and effects of these are coupled together and so, in general they cannot be interpreted independently. The most comprehensive examination of the physical phenomena and insights into the flow mechanisms around end-effectors is reported by [D1]. A summary of the key principles is given below.

By nature of its design, a large flap will pose as a significant obstacle to the incoming wave. A large pressure differential is established between the front and back face of the device, which created the driving wave torque on the device This pressure differential manifests itself as a difference in surface elevation level between the two faces. For a rectangular shaped flap, the fluid flows around the edge of the device from the high surface elevation level to the low surface elevation level. Evidence of this can been seen in Figure 39(a) where not only is the velocity magnitude at the sides large, but there is also a significant amount of flow tangential to the flaps front face several metres in from the edge. Not only does this large edge velocity increase the turbulence in this area (as seen before), but the direct flow path around the flap sides also distorts the surface elevation profile across the front face. As a result, the surface elevation takes on a convex shape which is highest in the centre of the flap and drops off towards the edges. Consequently, lowering the pressure different across the flap.



(a) Rectangular Flap (b) End-Effectors

Figure 40. (Top) Net pressure differential, (Bottom) Net torque per unit area across the face of the flap. The z and y axis denote the dimensions along the height and width of the flap.

In contrast to the rectangular flap, when protruding rounded end-effectors (“dog-bone”) are attached they pose a much more difficult flow path around the edge of the device. Evidence of this can been seen in Figure 39(c) where, inside the end effectors, the flow is normal to the flaps front face and cannot escape as readily around the edge of the device. In addition to that, the rounded profile of the end-effectors creates a more streamlined flow pattern and lower fluid velocity around the edge. These two effects combine to both: reduce the flow and turbulence around the edge of the device (as can be seen when comparing Figure 38(a) and (c)); and increase the surface elevation difference between the front and back face of the device. The increase in net pressure and thus wave torque induced on the flap is shown in top and bottom images of Figure 40 respectively. It can be seen that the pressure (surface elevation) is much more uniform and of higher magnitude between the end-effectors than across the rectangular flap. Consequently, the resultant torque which drives the flap is larger, owing to a better power capture performance of the flap with end-effectors.

[D1] experimentally tested the end-effector device at 40th scale in 3 different irregular sea states. On average, a 15% increase in power capture was observed with the benefits becoming greater as the wave height increases from 1.25m to 2.75m. It could be concluded here that circa 5% of this gain comes from the rounded edge shape and reduction in turbulence intensity and circa 10% from the increase in wave torque induced on the flap. However, as just discussed this latter effect is also coupled to the turbulence characteristics of the flow around the device.

Similarly, experimental wave tank tests conducted by [D2] also found a 15% increase in flap performance when large rounded end-effectors were attached. However, the authors only reported a marginal increase in the induced wave torque on the flap and concluded that the performance increase was due primarily to the reduction in turbulence and viscous losses. This lack of wave torque increase is in contrast to that just discussed. However, it must be noted that only a 12m wide flap was investigated by [D2]. As discussed previously, it is thought that viscous edge effects play a much more significant role in narrower flaps rather than wider flaps. This may somewhat explain the difference in qualitative behaviour. Some evidence of this has also been reported by [D2] where the percentage increase in performance was not as significant on a wider flap for the same size/design end-effector.

Experimental tests on a series of 18m wide flaps with different end profile shapes were conducted at 40th scale by [D4]. In each case, significant performance gains were reported, the most notable is a 52% increase with rounded end-effectors. See Figure 41 for a summary of the experimental test results.

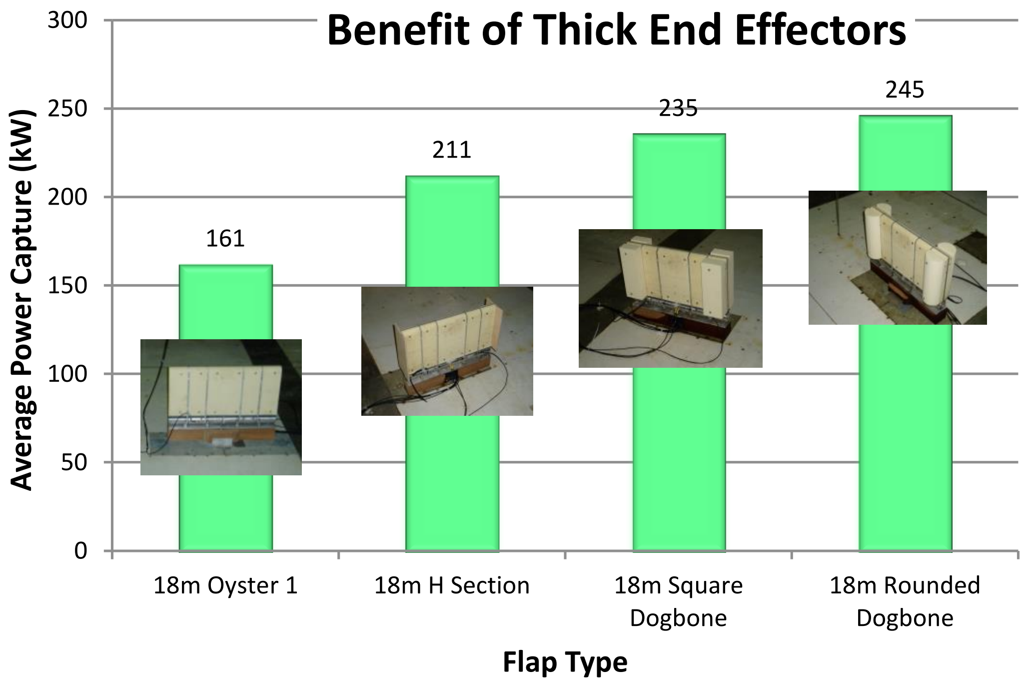


Figure 41. Performance gain of an 18m wide flap with different end-effector shapes. (Note however that the pitch stiffness of the flaps also increased with the inclusion of the end effectors. As a result, the performance gains are due to a combined effect of increased buoyancy and end-profile design)

It must be noted however that unlike the previous experimental results discussed, the inclusion of the end-effectors in these tests modified several properties of the device. The most notable was the buoyancy or pitch stiffness of the flap. Higher pitch stiffness is known to have a very beneficial effect of power capture. Thus, it is not possible to decouple the benefit of the end-effectors alone from these results. In addition, the original 18m wide reference flap is a very sub-optimal design. Thus, changes to such a sub-optimal design is likely to have a more dramatic effect on performance compared to an initially more optimised flap design, such as the large 26m wide, buoyant flap discussed previously.

An additional benefit of the inclusion of end-effectors (as reported by [D3]) is that the power capture performance can be increased without a proportional increase in the foundation loads on the structure (once the effect of larger flap buoyancy is accounted for). A similar conclusion was drawn by [D7] where specific flap and/or edge shapes have the potential to divorce the relationship between power modification and loading. In this study, various flap shapes were examined with an aim to reduce large impact loads on the flap structure. It was concluded that there are flap shapes which can reduce the impact loading on the structure and any performance losses are more than compensated by the reduction in load. Thus, delivering a WEC with a better loading/power ratio.

Summary

The inclusion of wide end profiles which restrict the flow around the edge of the device has a beneficial effect on power capture due to the 'flow entrapment' on the face of the device. This entrapment increases the driving wave torque induced on the flap. Furthermore, rounded end profiles have the additional benefit of effectively reducing the turbulent flow at the edge of the device, thus contributing to a performance increase.

The cause and effect of the wave torque increase and turbulent flow loss around the edges of a flap are strongly coupled together. Thus, they should not be examined or interpreted in isolation.

Some of the research results presented show preliminary evidence that the flap and/or edge shape can influence the power capture of the device without a proportional modification of the loads. This is in contrast to many of the other design features of a flap-type device, where power performance increases have been shown to be strongly linked to increases in structural loads. Thus, edge design features are a way to achieve better device performance without having to unduly increase the structural robustness of the device.

8.5 Outcome of the Research

Although it has been demonstrated that the inclusion of large rounded end-effectors can have a significant benefit to power capture of a flap-type device, the depth of this knowledge and the insights into what the key drivers are, were not fully understood to align with the development of the full scale Oyster800 device. Although APL made a formal decision to include rounded end-effectors to the device, their specific shape and size evolved as the detail engineering design progressed. Structurally, designing and attaching such large appendages to operate at full scale is by no means a straightforward task. In addition, there were many other design integrations to consider with the PTO system, device base frame and foundations, ballasting system etc. As the commercial deadlines at APL progressed, the design of the end-effectors morphed, primarily driven by manufacturing complexity and cost. As a result, their shape evolved to what was ultimately installed on Oyster800, as shown in Figure 33.

Disappointingly, this shape is far from what was required from a hydrodynamic performance perspective, yet the cost of fabrication was extremely high. A study was conducted by [D6] on the effect of removing these sub-optimal features altogether. It was found that there was a mere 1% reduction in power capture if they were removed, once the impact of having a narrower and less buoyant flap was accounted for. However, the Oyster800 design evolved in such a way that the end-effectors also had an important function of protecting critical ballast equipment. Thus, for this reason and to keep with commercial timelines this suboptimal design was kept and implemented.

The key lesson to take from this experience is the management of the design evolution as the device transitions from R&D to an engineering reality. Oversight of the functional requirements, commercial constraints and interdependencies must be stringently monitored during this iterative cycle. Thus, it is important to follow a structured systems engineering approach and maintain overview of the requirements. In addition, at the R&D/concept design stage, it can be detrimental to pursue overly elaborate WEC structures or modes of operation as the probability of commercially achieving these in reality is low.

8.6 References

[D1]. Asmuth, H., (2014), "The Influence of End Effector Shape on the Dynamics of the Oscillating Wave Surge Converter Oyster", *Bachelor Thesis, TUHH*.

[D2]. Henry, A., (2008), "The Hydrodynamics of Small Seabed Mounted Bottom Hinged Wave Energy Converters in Shallow Water", *PhD Thesis, Queen's University Belfast.*

[D3]. Henry, A., (2009), "OY02-DES-REP-INT-29 Further experimental testing of dogbone shape flaps", *Internal Report, APL*.

[D4]. Doherty, K., (2009), "OY02-DES-REP-INT-22 Investigation into the effect of vertical piles on the performance of an Oyster device", *Internal Report, APL*.

[D5]. Wei, Y., Rafiee, A., Henry, A., Dias, F., (2015), "Wave interaction with an oscillating wave surge converter, Part I: Viscous effects", *Ocean Engineering, Vol. 104, 185 – 203*.

[D6]. Henry, A., (2010), "101118 The Effect of Removing the End Effecters from Oyster 2a - APL-RD.FDR.04-REP-0070 - A1", *Internal Report, APL*.

[D7]. Schmitt, P., (2013), "Investigation of the near flow field of a bottom hinged flap-type wave energy converter", *PhD Thesis, QUB*.

9 (E) Use of Elastomers to Replace Flap Buoyancy

9.1 Research Hypothesis or Motivation

The net restoring torque of a pitching flap-type WEC, i.e. the mechanism by which a flap returns to its equilibrium position, is a key driver of its power capture performance. The net restoring torque (torque as the device operates in the pitch degree of freedom) is commonly referred to as 'pitch stiffness'. The pitch stiffness influences the velocity and phase that the flap oscillates back and forth with in the waves, thus affecting its power capture ability. If the pitch stiffness is too small, the flap moves sluggishly at low velocity in the waves. Conversely, if the pitch stiffness is too large, the flap will tend to act as a 'stationary' wall and barely move from its static equilibrium point. Thus, for a given flap size there is an optimal level of pitch stiffness which helps maximises the power capture of a flap.

For a typical fixed volume flap, the pitch stiffness is usually the resultant of the flap's mass-buoyancy distribution. The concept of pitch stiffness is however complicated for a surface-piercing fixed-volume flap. This is because the submergence of the flap (which induces a buoyancy moment) is continually changing as the flap rotates and the surface elevation fluctuates with the passing wave crest/trough. An illustration of this is shown in Figure 42. Thus, the pitch stiffness is described by a distribution of instantaneous values over the operational cycle of the flap and not just one value.

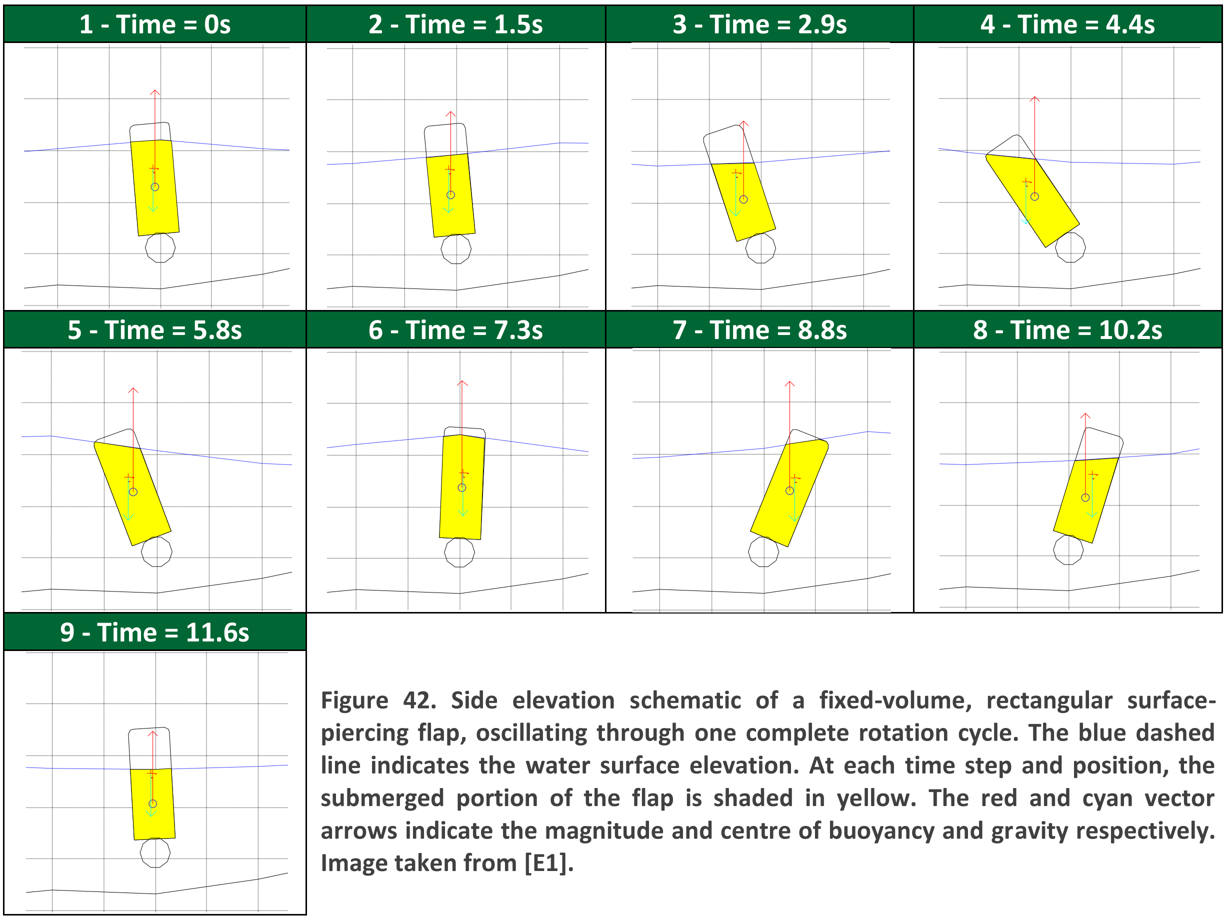


Figure 42. Side elevation schematic of a fixed-volume, rectangular surface-piercing flap, oscillating through one complete rotation cycle. The blue dashed line indicates the water surface elevation. At each time step and position, the submerged portion of the flap is shaded in yellow. The red and cyan vector arrows indicate the magnitude and centre of buoyancy and gravity respectively. Image taken from [E1].

For a buoyant surface-piercing flap, the pitch stiffness is inherently dependent on the flap shape and mass-buoyancy distribution along the flaps vertical axis. This makes optimisation of the pitch stiffness a complex and multivariate problem as factors such as: device size; water depth; freeboard size and shape; and material, all influence the instantaneous buoyancy. Optimisation of the pitch stiffness magnitude via flap shape modifications, brings with it other knock-on consequences in terms of loading and flow field distortion, as was discussed previously in Sections 6.4 and 6.5.

For Aquamarine Power, the motivation behind this research topic was to explore ways to decouple the pitch stiffness from the buoyancy of the flap. For APL's Oyster technology, the significance of divorcing the pitch stiffness from the buoyancy could lead to the following benefits (many of which would contribute to a significant reduction in cost):

- Significant reduction in flap volume.
- Less static heave load on the foundations of the device.
- Possible removal of a ballasting system, (required at the installation stage of a buoyant flap).
- Possible replacement of the WEC hinges (depending on the elastomeric solution designed).
- Possibility to achieve a constant or pre-defined pitch stiffness distribution
- More scope to tailor and optimise the flap geometry and design features independently. This reduces complexity and R&D effort.

Elastomeric materials were identified as offering a potentially feasible alternative mechanism to satisfy this functional requirement.

9.2 Year and Research Activity

- **2012 – Ref. [E2] – Experimental wave tank testing at 40th scale of a rubber-hinged flap.**

  Experimental wave tank tests were conducted on a 40th scale model of a thin, neutrally buoyant flap with the rotational hinge replaced with an elastomeric rubber material. Three different rubber configurations were tested which gave three different magnitudes of pitch stiffness. The flap dimensions were (full scale equivalent) 24m wide, 12.2m tall and 0.4m thick and it was tested in a set of 7 irregular 'performance' sea states and 1 'extreme' storm sea state. No PTO mechanism was modelled and so no power estimates could be made directly. However, the flap rotation and foundation forces were measured and the dynamic characteristics and loads compared to a similar size buoyant flap, see Figure 43.

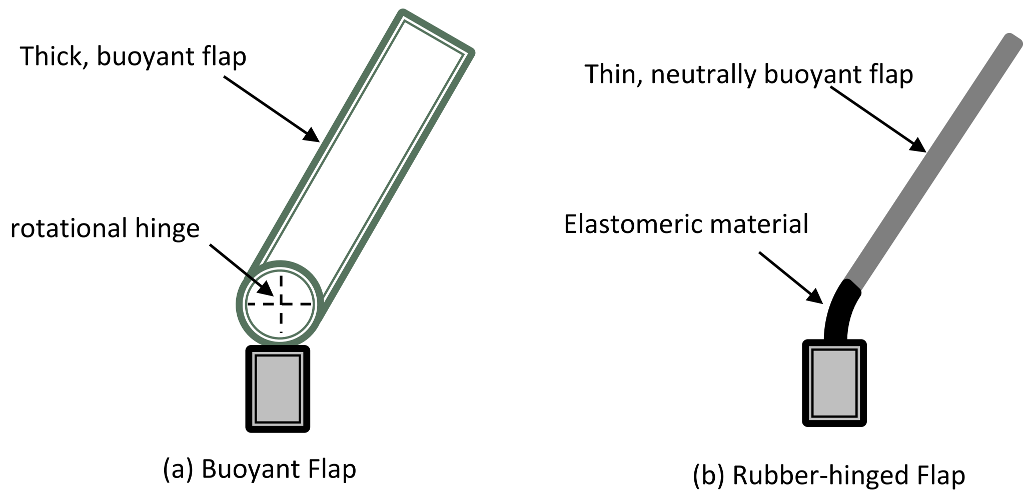


Figure 43. Schematic of: (a) a fixed volume buoyant flap and (b) a neutrally buoyant thin flap with a rubber hinge.

This series of preliminary tests was a first-pass exploration of the motion and load characteristics of a rubber hinged flap and the differences relative to a buoyant device. It should be noted that for the tests, a readily available rubber material was selected purely based on its ability to deliver a pitch stiffness of a similar order magnitude as the buoyant reference flap. No detailed specification or investigation of the elastomeric material properties was made prior to testing.

Due to the preliminary nature of the tests, no direct quantifiable conclusions could be made about the power capture performance of the device. However, insights into the dynamic behaviour (rotation and velocity characteristics) of the flap were made, from which estimates of the performance impact could be postulated. In addition, the characteristics of the foundation loads on such a flap concept were demonstrated.

- **2012 – Ref. [E3] – 'Desktop' calculation of the effect an elastomeric hinge has on the loading on the foundations of the Oyster801 concept.**

A short desktop analysis which estimates the impact an elastomeric hinge design might have on the foundation loads of a flap structure. The study was based on the 3rd generation Oyster design, namely Oyster801, and the fatigue and ultimate loading conditions of this device were used as the basis for the calculation.

The elastomeric hinge design considered is same as that shown in Figure 43(b), where the rotational hinge has been removed and the flap's motion is now permitted through distortion of an elastomeric material. The calculation methodology assumes that the entire pitch restoring moment (equivalent to the net buoyancy moment of the Oyster801 flap) is now reacted by the foundations (via the elastomeric material), rather than inducing rotational movement about a hinge bearing. This additional moment is added to the original Oyster801 foundation loads and the resultant fatigue and ultimate load conditions recalculated.

The results give a high-level estimate of the foundation loads, under the assumption that the pitch stiffness magnitude achieved via the elastomeric material was the same as the net buoyancy moment of the Oyster801 flap.

- **2011 – Ref. [E4] – Material feasibility study (conducted by an external 3rd party).**

A high-level material feasibility study which identifies: potential elastomeric hinge design configurations for the Oyster device; fatigue characteristics and other key properties of elastomers; required material volume; and key research groups which could aid in the further material testing and development of the concept.

- **2012 – Ref. [E5] – High-level engineering concept designs of an elastomeric hinge.**

A summary document which collates and presents the high-level design requirements, technical challenges and summarises the preliminary design concepts (as identified in [E4]) of an elastomeric hinge compatible with an Oyster type device.

9.3 External Influences on the Research Programme

Elastomeric materials research, with the aim to replace the structural buoyancy of the flap, was initiated around the same time APL were progressing the FEED of the Oyster801 device (their 3rd generation concept). Thus, a lot of emphasis was put on assessing the feasibility of incorporating elastomeric material into this device. This may have restricted or narrowed the design scope of the research somewhat.

9.4 Results and Conclusions

1. **The restoring moment provided by an elastomeric hinge is reacted through the foundations of the device, creating an additional loading mechanism.**

   By testing a rubber-hinged, neutrally buoyant flap with three different levels of elastomeric pitch stiffness, the experimental results reported in [E2] confirms that the restoring moment is reacted through the foundations of the device. The larger the pitch stiffness the greater the foundation loads recorded, due to the higher strain in the elastomeric material, see Figure 44.

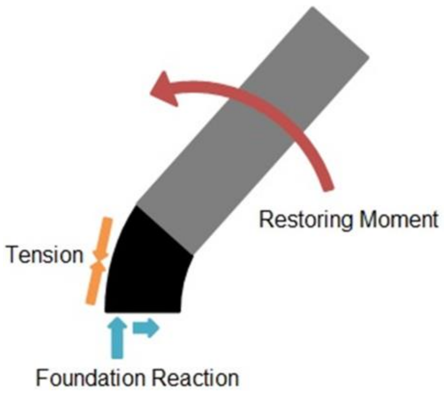


Figure 44. Simple force diagram of an elastomeric hinge.

   The desktop calculations presented in [E3] indicates that if an elastomeric hinge was designed with a pitch stiffness, equivalent to the net buoyancy moment of the Oyster801 flap (circa 50 MNm/rad when fully submerged), it would significantly increase the fatigue loading on the foundations by up to circa 60%.

   A similar order of magnitude increase was estimated for the ultimate loading under extreme storm wave conditions. However, this result only relates to the 'pulsating' element of the foundation loads, which are defined to occur on the same time scale as the wave and/or flap oscillatory period. The short duration 'impulsive' foundation loads, typically associated with a wave slam or slap event, were shown to decrease when an elastomeric hinge is considered. Conceptually, this result seems plausible as the compliance introduced by the elastomeric material may help absorb impulsive shock loads and they are not transferred through to the foundations. However, it must be pointed out that there are very large uncertainties in the impulsive load data used by [E3]. This measurement is heavily influenced by the structural characteristics and vibrational frequency of the experimental scale model itself. At the time of this study, unresolved experimental issues existed in the test data. Thus, no quantitative conclusion should be drawn from this data. A more in-depth discussion of the issues associated with measuring impulsive loads is presented in Section 11.

2. **Material hysteresis influences the dynamics and operation of a flap with an elastomeric hinge and is expected to only have negative effects on device performance.**

The effect of hysteresis on the motion of a rubber-hinged flap was reported in the experimental wave tank test results of [E2]. It was observed that as a sea state test progressed, the flap would oscillate about an increasingly more landward position. This subsequently promotes more wave overtopping and thus energy loss. Although there was no predefined specification of the rubber properties used in these tests, qualitatively it does highlight the importance of designing for (or mitigating against) the effects of hysteresis, which is inherent in most elastomeric type materials. A continually evolving flap equilibrium position may have serious consequence for the PTO mechanism, the power capture performance and general operability of the device.

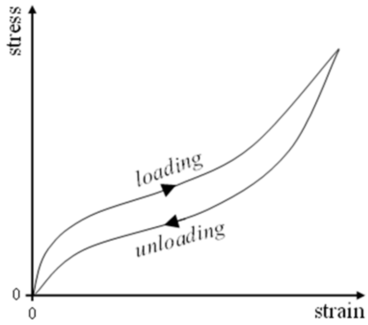
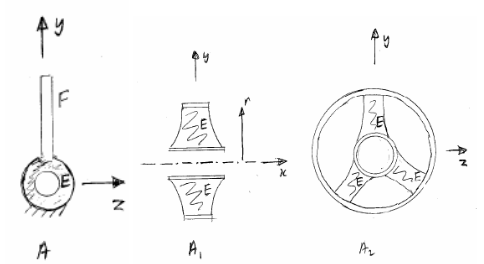
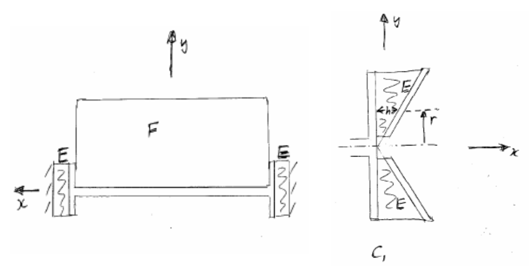


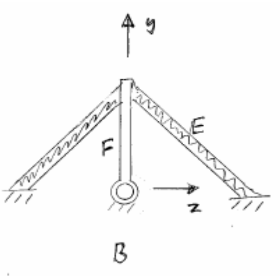
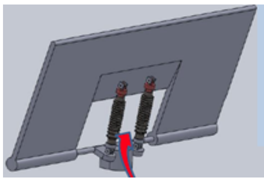
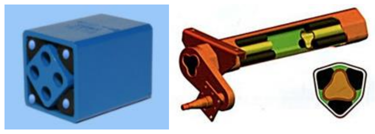
Figure 45. Typical Hysteresis loop

3. **Fatigue cracking of the material was identified as a key design driver in the specification and implementation of an elastomeric hinge solution on a flap-type device.**

This was identified and supporting calculations presented in the material feasibility study of [E4]. At the time this report was released, it emphasised that the specified design criteria (load magnitude and number of cycles) is very much a new and demanding area for elastomers. With limited engineering data in existence to aid in the design process, it is advised that extensive material testing is required to gain further confidence in the use of this material under such demanding conditions.

4. **Several elastomeric-hinge design concepts have been identified which could be feasible for implementation on a large (26m wide) flap-type device**

1. Rubber bushes	**2. Rubber torsion disc**
 An inner housing is rigidly fixed to the sub-structure; an outer housing is rigidly fixed to the flap, and an elastomer is rigidly fixed between outer and inner housings. The elastomeric bushes provide a restoring moment through shear resistance. Fatigue performance could be improved by radial or circumferential pre-straining. Initial sizing estimates that a pair of 1.5m OD, 0.5m ID and 2.5m long bushes could deliver the 50MNm restoring moment specified.	 The elastomer is axially mounted onto the flap and provides the restoring moment through torsion. Initial sizing estimates that a pair of torsion discs with a 3.2m OD and length of 1.6m could deliver the necessary 50MNm restoring moment specified for the Oyster801 device.

3. **Linear/Nonlinear springs**	4. **Trailer axle**
  An elastomer could be used as a spring in tension or compression. This would potentially be reinforced using fibres or steel cord to change the spring properties, or else with innovative thermoplastic materials and designs.	 In some trailer axle suspension applications, rubber cartridges are cryogenically frozen between a shaft and outer housing. The restoring moment is provided through compression of the rubber cartridges. Off-the-shelf square shaft and triangular shaft axles typically achieve extreme rotations of 42.5° and 80° respectively. It is expected this rotational range could be improved since trailer axles are not designed specifically to maximise rotational range.

These concept ideas were first identified by [E4] and then subsequently discussed in [E5] in the context of its application to the Oyster801 design and the key technical challenges which need to be explored further to demonstrate their applicability. The work done on these concepts only brought it to a TRL of at most 2, with the basic principle and speculative application identified and some analytic calculation complete.

5. **With a thorough design, it seems plausible that a flap with an elastomeric hinge, (which completely replaces structural buoyancy) could deliver a comparable power capture performance as a buoyant flap-type device.**

   Although there is no direct quantifiable evidence of this from the research referenced, preliminary indications of device dynamics (reported in [E2]) would suggest that with an innovative flap structural design and careful material specification and configuration, an elastomeric hinged flap could deliver a comparable performance to an equivalent buoyant flap.

   Only very high-level studies and preliminary tests have been conducted by APL on this topic. Thus, given the broad design and optimisation envelope surrounding the application of elastomers for this purpose, it is expected that an adequate design solution exists. It is postulated here however that the likelihood of an elastomeric hinge to deliver an improvement in performance is low.

   As a first-pass attempt at a techno-economic analysis, a high-level cost analysis was reported by [E6] as part of the Oyster801 project. An optimistic cost saving of €450k was estimated over the existing Oyster801 flap design due to: a) a significant reduction in the volume and material in the flap; b) replacement of the main hinge bearings; and c) the removal of a ballast system (as it is envisioned that the flap could be close to neutrally (or even negatively) buoyant). However, it is felt this is a very optimistic view of the cost saving potential as the cost implication of significantly increasing the foundation loads (as discussed in point 1 earlier) has not been incorporated. However, it does highlight that there are cost saving potentials within this technology which, if achieving a similar power output, could result in a more commercially attractive solution. However, the economical consequence of incorporating elastomers must be evaluated across the entire WEC system to avoid a 'cost water-table' effect.

9.5 Outcome of the Research

Only high-level feasibility studies were completed by APL on this topic. This lead to the development of some working models which can calculate the characteristics of an elastomeric hinge design, including necessary volume, geometry, hysteresis and stress and strain properties etc. However, the lack of elastomeric material expertise in-house in APL and the fact that this topic was not ranked as high up the time priority list as other activities ongoing within the company at the time (e.g. installation, commissioning and operation of Oyster800 at EMEC), meant that it was on a slower R&D scale and subsequently never advanced past a TRL level of 2, at best.

It is felt that there is a lot of merit reinitiating more research into this topic advancing the investigations well beyond the preliminary scoping studies presented here. The development and application of this technology has the potential to deliver a cost reduction of a flap-type WEC and indeed other related structures such as a hinged-raft WEC.

Another potentially useful application, which was not elaborated on here as it was outside the scope, is the use of elastomers in swivel joints in hydraulic circuits. Such a concept was also presented in [E5] and may aid in the interface design of a hydraulic PTO systems and the WEC prime mover.

9.6 References

[E1]. MacLeod, A., (2012), "APL-RD.FDR.04-REP-0117 - 120202 - Oyster 802 Flap Shape and Pitch Stiffness Analysis - A1", *Internal Report, APL.*

[E2]. Perrin, A., (2012), "120704 Rubber Hinge Flap APL-RD.OY802.08-REP-0004 A2", *Internal Report, APL*.

[E3]. Bryans, G., (2012), "120414 Pitch returning loads - APL-RD.OY802.08-REP-0002 - A2.docx", *Internal Report, APL*.

[E4]. Coveney, V. A., (2011), "Coveney Report v2b", *External report prepared for APL*.

[E5]. Perrin, A., (2012), "120326 - Working Document on Elastomeric Pitch Return Options - APL-RD.OY2C.08-TN-0003 - A1", *Internal Report, APL*.

[E6]. Bryans, G., (2012), "120406 Cost reduction through an elastomeric pitch return mechanism - APL-RD.OY802.08-REP - A3", *Internal Report, APL*.

10 (F) Impact of Bio-fouling on a Flap's Power Capture

10.1 Research Hypothesis or Motivation

Figure 46. Bio-fouling on Oyster800 after a nine month period of submergence prior to first operation

Bio-fouling is referred to as the undesired development of microbial layers on surfaces and corresponds to the spontaneous colonisation of a submerged object by fixing organisms. It is divided into micro-fouling, which relates to the formation of a biofilm and the adhesion of bacteria, and macro-fouling, which categorises the attachment of a broad range of bigger organisms such as barnacles, mussels, polychaete worms, bryozoans or seaweed. The onset of bio-fouling on a submerged structure is essentially unavoidable, especially in the oxygen and nutrient rich regions of high wave activity where WECs are design to operate. WEC devices can create new habitats and colonisation zones for marine vegetation. This is especially true for a bottom-hinge flap device where most of the structure is submerged close to the seabed. Thus, an array of devices could essentially turn into an artificial reef unless targeted human intervention was initiated.

As well as the practical bio-fouling issues relating to the maintenance, operability and integrity of device components, APL investigated the potential impact macro-fouling may have on the power capture of the device. This is the topic discussed in this section. Quantification of this is important in the large-scale development of the WEC technology. If performance is significantly affected, thorough cleaning and preventative maintenance activities may have to be scheduled which could significantly increase the OPEX of a project, especially on a large scale WEC array/farm.

10.2 Year and Research Activity

- **2013 – Ref. [F1] – 40th scale experimental wave tank tests of the Oyster800 device with a significant amount of synthetic 'kelp' (macro-fouling) attached to the flap.**

  Experimental wave tank tests were conducted at the wave tank facility at Queens University Belfast (QUB) on a 40th scale model of the Oyster800 device. The tests examined the effect large kelp growths, both attached to and surrounding the Oyster800 flap, have on the device's hydrodynamic performance. (Note: Kelp, or macro-algae is known to dominate the intertidal and subtidal regions (to a depth of circa 30m) where an Oyster device is designed to operate. In particular, it is the *Laminaria* species of kelp which mostly inhabits the EMEC site where Oyster800 is installed).

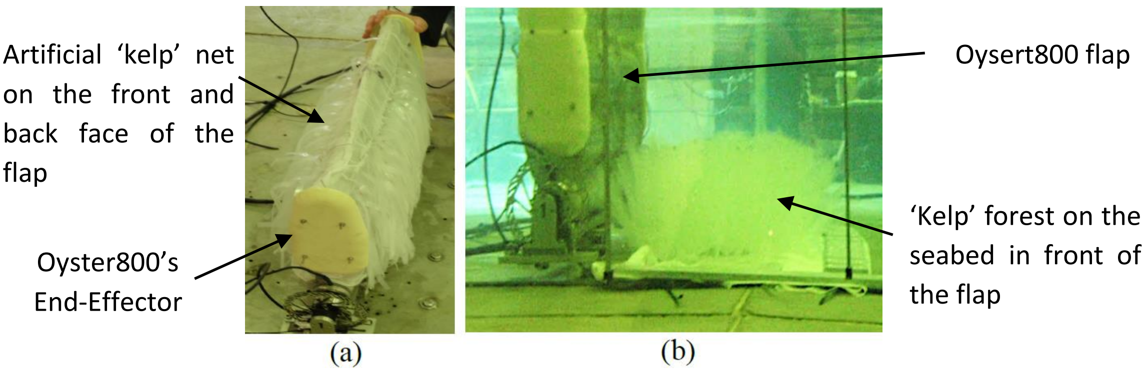


Figure 47. Oyster800 model with 'kelp' (a) on the flap and (b) on the seabed in front of the device

The kelp was modelled with individual plastic strips sown onto a net, which could then be attached to the scale model, see Figure 47(a). Similar to real kelp, the plastic strips were almost neutrally buoyant when submerged and so their attachment to the flap did not alter the device's pitch stiffness.

Tests were performed in 4 irregular sea states, representative of the conditions that contribute the most to Oyster800's annual energy production. In each sea, three different kelp attachment configurations were tested: (1) on the landward side of the flap only; (b) on the seaward side of the flap only; (c) on both sides. In each configuration two different kelp lengths were examined, 6m and 2m (full scale equivalent dimensions). The PTO damping torque on the flap was varied in each sea state to optimise the power capture and the power compared to the benchmark Oyster800 flap without any kelp attached.

During the test programme, a gap underneath the hinge line of the device was present. An additional experiment was executed where a 'kelp forest' (i.e. the plastic kelp net) was attached to the seabed immediately in front (seaward side) of the device, see Figure 47(b). Again, the power capture of the device was measured in the wave conditions with and without this forest present to assess if it would mitigate the power loss underneath the hinge line i.e. block the gap. See Section 0 for more details of the gap underneath the flap.

- **2011/2012 – Ref. [F2], [F3], [F4] – Mathematical model of the bio-fouling process and an assessment study of the plausible extent of bio-fouling on an Oyster device.**

In this work, a mathematical model was developed from first principles to describe the micro- and macro-fouling process. This framework enables predictions of the growth rate and volume/mass of various bio-fouling species, incorporating seasonality effects. The model was used to examine the potential extent of bio-fouling on Oyster1 (APL's first full scale machine installed at EMEC) over a 1,5,10 and 20 year period. An assessment of the additional mass of bio-material that could grow on the flap was made for different growth zones cases, ranging from full flap colonisation to growth only between the horizontal tubulars of the Oyster 1 device.

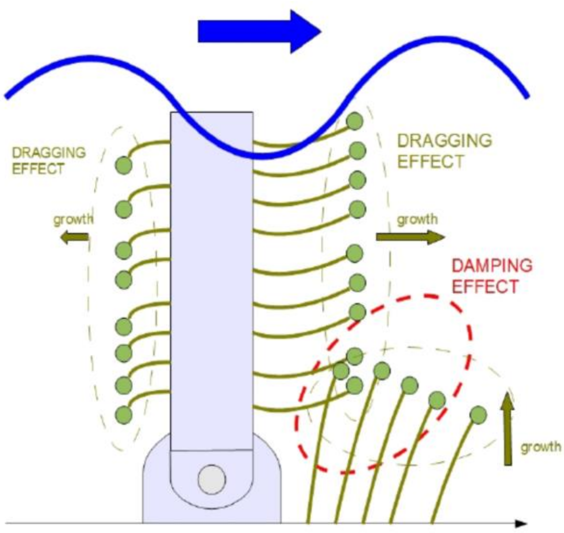


Figure 48. Expected long-term growth on a flap

Supplementary qualitative discussions are also provided on key issues of bio-fouling on the performance of WECs and the prevalent species of marine vegetation in Irish and UK waters. Bio-fouling growth predictions are made for four different classifications of nearshore WEC concepts, including surging and heaving devices.

- **2014 – Ref. [F5] – A summary review and discussion of the bio-fouling challenges and considerations facing wave energy converter development.**

  This is a thought provoking review paper which addresses many challenges facing wave energy converters operating in the marine environment. Particular focus is given to the WEC's interaction with the marine eco-system. This is a useful narrative to review to get a broad overview of bio-fouling issues that could be factored into the early design stage of a device.

10.3 External Influences on the Research Programme

Apart from some project coordination from APL staff, the bulk of this research was conducted by the marine research group in UCD (one of APL's collaborative partner institutes). Thus, the research was largely under the control of UCD's resource.

10.4 Results and Conclusions

1. **Within 5-10 years, the extent of bio-fouling on the submerged portion of a flap can reach over 10% of the flaps original mass (if no manual intervention/cleaning is engaged).**

   The growth models of [F2] and [F3] estimate the mass of bio-material that could grow on the submerged portion of an Oyster type flap could be between 10% and 20% of the original flap mass. It should be noted however that this mass estimate is the *non-submerged* mass of the bio-material. If for example the bulk of the bio-fouling was a macro-algae such as kelp, which is almost neutrally buoyant when fully submerged, then this added bio-material may not actually affect the pitch stiffness of the device. The metric does provide a quantifiable reference for the extent of bio-fouling possible on a flap if left 'unattended' for several years. It should be noted though that algae losses are only considered through mortality and no removal of kelp via external influences such as storm waves are considered in the model.

2. **The power capture of a flap is reduced by circa 15% if the seaward face of the flap is colonised with mature kelp. Whereas only a minimal reduction in power is experienced if kelp is attached on the landward face.**

   The experimental results of [F1] consistently show a significant decrease in power capture of 15% across all sea state tested if a large amount of kelp (neutrally buoyant) is attached on the seaward face of the Oyster800 flap. It is thought that the kelp significantly changes the flow field surrounding the flap and potentially the drag experienced by the device, which in turn distorts the dynamic behaviour and performance. However, no further insights into the precise mechanism have been obtained.

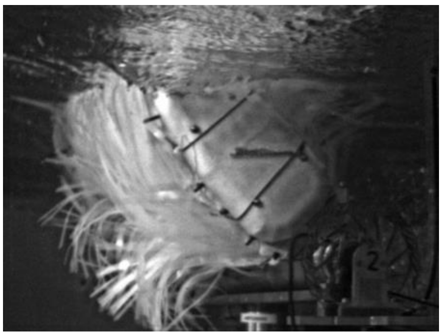


Figure 49. Underwater image of the Oyster800 model with '6m kelp' attached to the seaward face of the flap

   It must be stressed however that the intricate details of scaling and drag effects have not been considered in the tests when modelling the kelp on the 40th scale flap model. Thus, a more in-depth investigation would be required before definitive conclusions could be extrapolated to full scale. Nevertheless, the tests do provide insights into a large asymmetry in the flow features and drag characteristics on the front and back face of the device. With a distortion of the flow field on the seaward face having a much larger detrimental effect of power capture. In addition, it was also found that even if the length of the kelp was reduced by a factor of 3 (i.e. from 6m to 2m), the same reduction in power capture was experienced. This is despite the fact that the drag characteristics should be considerably different in this case.

Despite some outstanding issues concerning the scaling of the modelled kelp in the test, key qualitative insights can be drawn. The tests show that heavy levels of kelp/marine growth on the seaward face of the device can distort the incident flow field, which in turn can significantly affect the power capture performance of the flap.

3. **A permeable kelp forest in the region in front of and underneath the hinge line of the device is not an effective mechanism of blocking the gap to improve power capture performance.**

   The test results of [F1] demonstrate that no improvement in power capture is observed if the gap underneath the hinge line of the flap is 'blocked' with a kelp forest (see Figure 47(b)). Although it is expected that the kelp forest will distort the flow in this region to some degree, it is postulated here that the permeable nature of the forest does not facilitate an increase in the pressure difference between the front and back face of the flap. It is via this mechanism that the flap improves its performance, see Section 0 for details.

10.5 Outcome of the Research

Aside from the knowledge gained on this topic, no actionable activities were performed by APL following on from this research.

However, the insights derived from this preliminary analysis would suggest that further investigation should be conducted into the effects of bio-fouling. Evidence shows that the performance of a device could be significantly affected by heavy levels of macro-fouling and the extent of bio-fouling on a large array of devices can be noteworthy. This may lead to a significant increase in the OPEX of a WEC farm project.

A key influence on the success of any future bio-fouling research will be access to real site data such as surveys and marine samples etc. Such data is essential in order to design, calibrate and validate any predictive models and assessment tools. To date, such data is sparse within the wave energy community. However, opportunities do exist to fill such a data gap. For example, APL's Oyster800 device was ballasted down and locked to its based frame in September 2014, where it has remained ever since (up to the time of this report). The commissioning of a marine survey of this device would capture a host of valuable information. Measurements of the extent of bio-fouling, marine growth and vegetation and a comparison to marine surveys conducted at the site prior to device installation, such as [F6] and [F7], would provide a wealth of valuable knowledge for the marine and wave energy community and boost future research efforts.

10.6 References

[F1]. Tiron, R., *et al* (2013), "An Experimental Study of the Hydrodynamic Effects of Marine Growth on Wave Energy Converters", *Proc. ASME 32nd Intl. Conf. Ocean, Offshore & Artic Engineering (OMAE). Nantes, France*.

[F2]. Pinck, C., (2011), "Biofouling on Wave Energy Converters: Application to Oyster", *Internal project report, APL – UCD – Ecole Polytechnique*.

[F3]. Tiron, R., (2012), "Is Biofouling a Critical Issue for Wave Energy Converters?", *Internal presentation, APL – UCD*.

[F4]. Tiron, R., *et al*, (2012), "Is Biofouling a Critical Issue for Wave Energy Converters?", *Proc. 22nd Intl. Offshore & Polar Eng. Conf. (ISOPE), Rhodes, Greece, June 17 0 22*.

[F5]. Tiron, R., (2015), "The challenging life of wave energy devices at sea: A few points to consider", *Renewable and Sustainable Energy Reviews, 43, pp. 1263-1272*.

[F6]. Xodus Group, (2010), "OY02-DES-RH-XOD-REP-0003 - Seabed Impact Assessment - B1", *External report commissioned for APL*.

[F7]. Aspect, (2010), "A4619_ROV Report _Draft.pdf", *ROV Survey of Oyster800 site*.

11 (G) Assessing Wave Slam on Flap-Type Devices

11.1 Research Hypothesis or Motivation

Wave slam is a critical loading mechanism which must be considered in the design of any surface piercing WEC. This is particularly true for a surface piercing flap-type device, where such an event is of paramount importance to the structural integrity of the device. APL identified quite a unique slamming mechanism on their large flap-type device which occurred in storm wave conditions. The event is illustrated in Figure 50, which can occur quite readily in a sea state with a return period equal to or above 1 year.

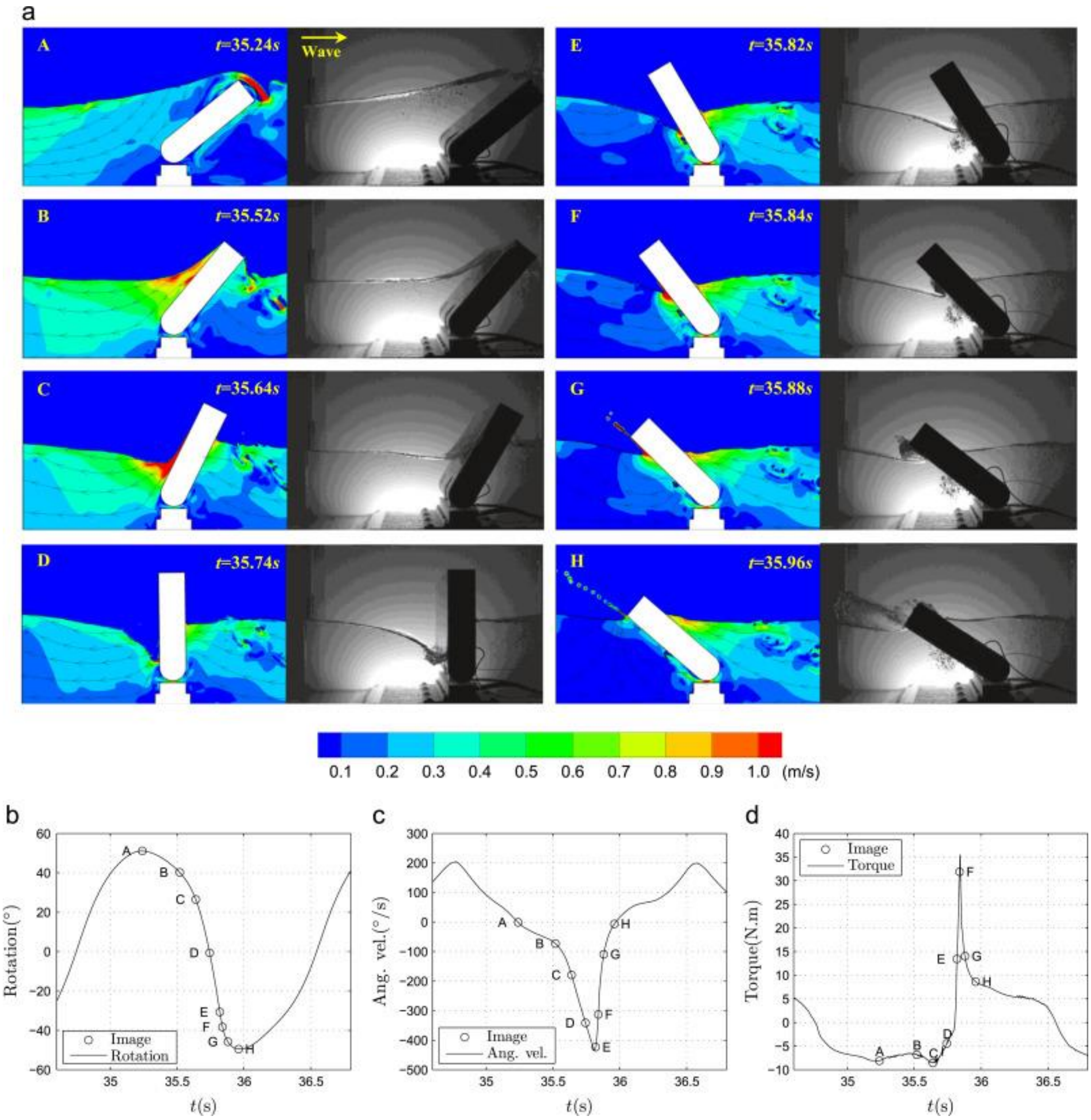


Figure 50. 2D illustration of a slamming event on a flap-type device. (a) CFD-Experimental pictures (A – H) depicting the evolution of the event. (b) flap rotation angle, (c) flap angular velocity and (d) induced pressure torque, during the event with the corresponding pictures indicated with the labels (A-H). Experimental tests and CFD simulations were conducted at 40th scale, which also corresponds to the values quoted on the graphs. Image taken from [G1].

In summary, the event is created when the flap moves back in the seaward direction into the trough of an oncoming wave (following the passing of the crest of the previous wave). The water 'drains' away from the seaward face of the flap (see Figure 50(a) frames C-D). With little fluid resistance on the seaward side, the flap is accelerated into the wave trough causing an impact at the lower region of the flap (Figure 50(a) frame E). A fluid jet is then formed which travels rapidly up the face of the flap (Figure 50(a) frame F) bringing with it an evolving zone of high pressure (akin to a water entry problem). Finally, the fluid jet is ejected from the flap once the front face becomes fully submerged.

For APL, this critical event had several significant effects on the design of a flap. The first stems from the magnitude of the localised impact pressures on the flap itself. This will affect the flaps structural design and integrity, choice of material etc. Secondly, following on from the slam event, load distribution and transfer through the structure is critical, especially in the foundation design. Finally, such an impulsive load may also have secondary effects such as shock loading on sub-components and the possible triggering of natural vibrations of the entire structure itself.

Wave slam has been studied before in other marine applications such as harbour, breakwater and ship design. However, a large flap-type WEC has fundamentally very different operating principles than these applications. So, although this can be classified as a slamming event, it is not a 'classical' wave impact event where a wave hits an object. It is a highly complex and variable phenomenon with a multitude of processes combining to form the complete event. The subtly unique characteristics of this event have resulted in only a limited amount of direct transferable knowledge from other marine applications and historic research. Thus, APL embarked on and invested a significant amount of R&D resource into examining this phenomenon over a 3-4-year period. The research involved the expertise of many of APL's collaborative institutes such as: QUB, UCD, TUHH, École Central de Marseille, HR Wallingford etc. emphasising the expansive and complex nature of this issue.

The knowledge and insights gained on the specifics of this slamming event extend well beyond the scope of what can be discussed in this report. Rather, this section focuses more on describing the various techniques and analysis methodologies developed and used by APL to gain insights into the problem. However, the comprehensive series of report references given will also enable the reader to learn more about the particularities and fundamental mechanisms of this slamming event if desired.

11.2 Year and Research Activity

- **2013/2014 – Ref. [G2], [G3] - Characterisation of the slamming event on a flap-type device using 3D experimental and numerical CFD techniques.**

  Experimental tests were conducted on a 25th scale model of a flap-type WEC at the wave tank facility at QUB. The high-level dimensions of the flap were similar to the Oyster800 device, i.e. 26m wide, 12m tall, in a water depth of 13m and with a hinge depth of 9m (full scale equivalent dimensions). The flap was tested in large waves; typical of the storm conditions a flap would be expected to experience during is operational life. Slamming events with the characteristics of that described in Section 11.1 were first observed and documented through this research. High-speed camera images (both above and below the water surface) of the event were recorded along with the flap rotation and some discrete pressure measurements on the front a back face of the flap.

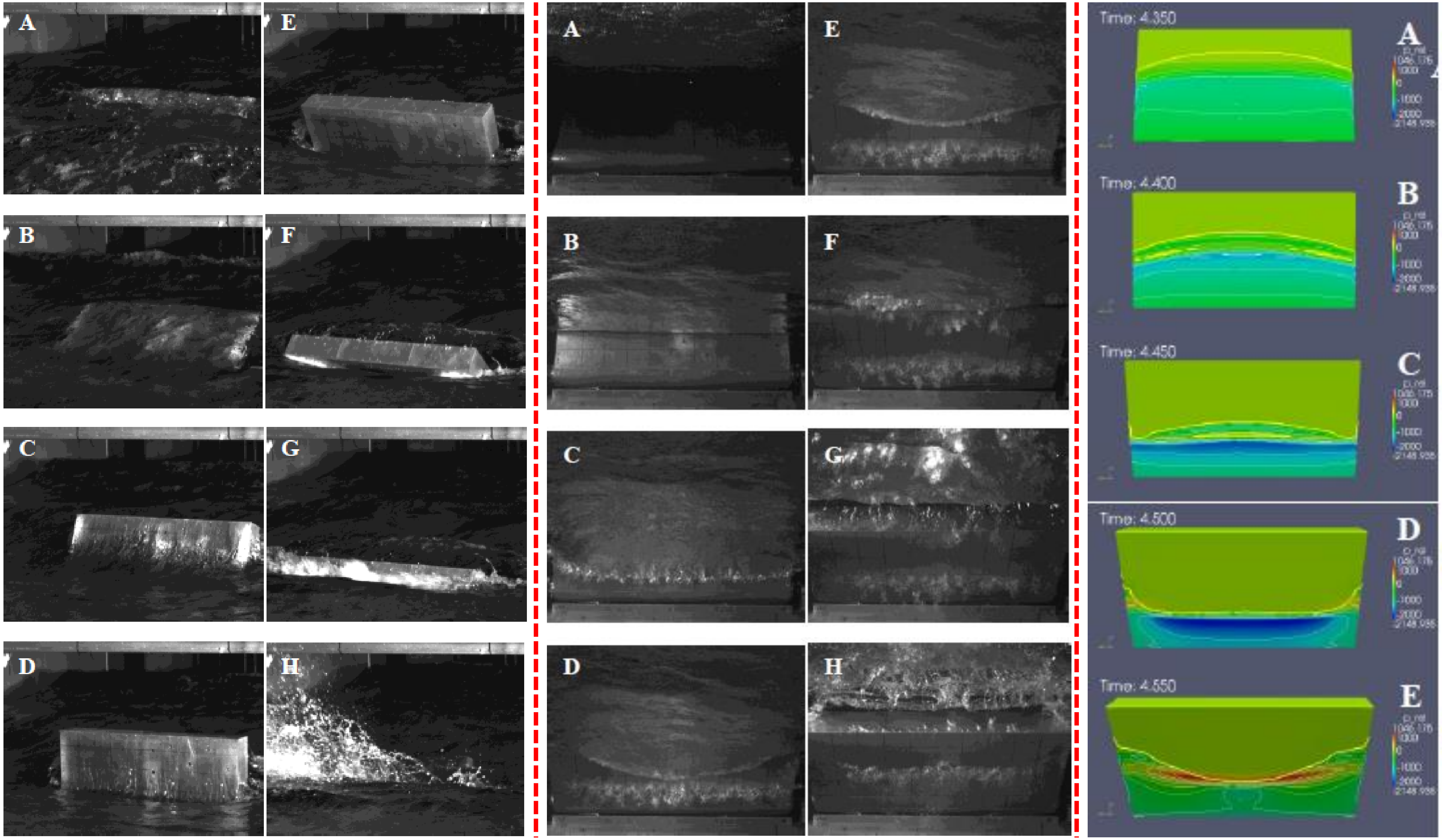


Figure 51. Time evolution images of the wave slam event on an experimental 3D flap model (left) above the water surface, (middle) below the water surface looking at the seaward face of the flap. The coloured images on the right are the equivalent CFD simulation results (OpenFOAM) visualised on the seaward face of the flap. The colour map represents the fluid pressure on the flap structure and the thin yellow line denotes the profile of the free surface on the face of the flap.

Independent CFD simulations using: (1) a Volume Of Fluid (VOF) method developed in OpenFOAM; and (2) a meshless Smooth Particle Hydrodynamic (SPH) technique; were also developed. The numerical simulations were compared and validated against the experimental results. Figure 51 shows an example of the high-speed camera images recorded during the experiments along with the predictions made by the CFD model (OpenFOAM).

- **2014 - 2016 – Ref. [G1], [G4], [G5], [G6] – 2D Experimental and numerical analysis of the wave impact characteristics on a flap-type device.**

Following on from the identification, visualisation and characterisation of the slamming event in 3D. An extensive research programme was designed and executed which investigated the event in 2D. The motivation was to try and simplify the problem somewhat in order to gain better insights into the various processes and driving mechanisms behind this phenomenon.

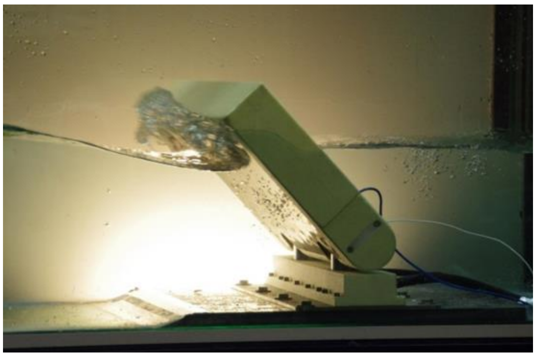


Figure 52. Experimental flap model in 2D tests

Experimental tests were conducted at 40th scale in a narrow wave flume in École Centrale de Marseille, where the flap blocked the entire width of the flume, see Figure 52. Again, high-speed camera images of the event were recorded along with flap rotation, foundation loads and a single point pressure measurement on the front face of the flap. Quantitative analysis results, along with a bespoke image processing technique are presented in [G4]and [G6]. The presentation slides of [G5] give a good overview of the background to the wave slam problem along with an excellent visual summary of the experimental research conducted.

CFD simulations of the 2D slam scenario were also conducted using the VOF method, modelled in the commercial package ANSYS FLUENT. Numerical results were compared and validated against experimental data and key insights into the driving mechanisms acquired. Figure 50 shows an example of the 2D experimental and numerical results obtained from this research programme.

- **2015 - 2016 – Ref. [G7], [G8], [G9] – Experimental wave slam pressure measurements on the front face of a flap in 2D, 3D and 'pseudo-3D' using 40th scale wave tank tests.**

Building once again on the knowledge and insights gained from previous research, a series of sophisticated experimental tests were conducted on a heavily instrumented 40th scale flap model. The instrumentation design focussed heavily on measuring the pressure distribution across the face of the flap during an impact event. A large number of PCB piezoelectric 112A22 dynamic pressure sensors were embedded into flap face with a high spatial resolution. In addition, non-invasive conductivity strips were also put on the faces of the flap to record the instantaneous surface elevation on the structure. This was in addition to directly measuring the flaps rotation, angular acceleration, foundation loads in six degrees of freedom and high-speed camera images during the event. See Figure 53 for an illustration of the instrumentation design.

The 2D tests reported in [G7] focused on assessing the vertical distribution an evolution of the pressure on the front face of the flap during a slamming event. It correlated the evolving pressure to the fluid jet velocity.

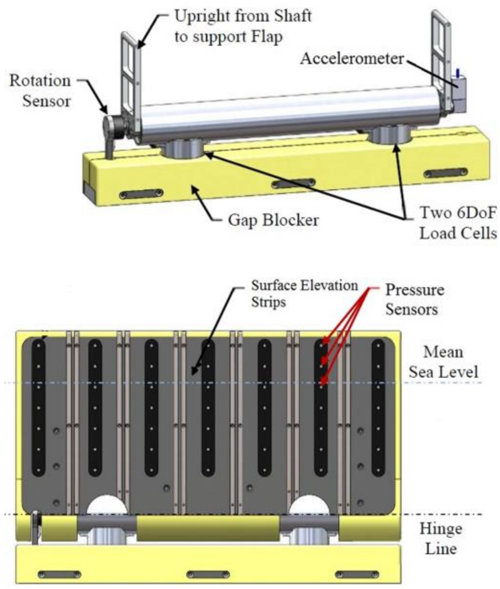


Figure 53. 40th scale model instrumentation. (top) flap foundation and hinge line sensors. (bottom) Flap front face sensors.

The results and insights of the slamming event reported from the 3D testing of [G8], are amongst the most advanced of all the research conducted under this programme. Results show that the slamming event is dependent on both the wave height and wave frequency, as well as being heavily influenced by the natural frequency of the device itself. The spatial distribution and variations in pressures across the face of the flap has been shown for the first time through physical measurements. Key insights into the repeatability of the slam event and robustness of the experimental configuration and instrumentation design are also provided.

Finally, a novel experiment was designed and tested by [G9] at the wave tank facility of QUB. Here the 3D flap model was split in two and positioned next to the glass wall of the wave tank (with a small gap between the flap and the wall which ensured friction did not adversely influence the motion of the flap). Thus, the wave tank wall could be thought of as a symmetry plane. This experimental design is labelled '2½D' or 'pseudo-3D' tests as the configuration combines the feature of both tests configurations. The motivation behind this pseudo-3D design was to try and marry the visualisation benefits of 2D testing with the physically realistic behaviour of 3D testing. Figure 54 shows some of the high-speed camera images which compare the 3D and 2½D experimental tests conducted.

A detailed comparison of the flap dynamics, features of the water surface elevation and impulsive pressures experienced by the flap in 2D, 2½D and 3D is made by [G9]. The results show significant differences in the pressure magnitude and characteristics between 3D and both 2D and 2½D. The flap dynamics and water surface elevation are also significantly different between the 3D and 2D cases with the 2½D exhibiting features of both of these scenarios.

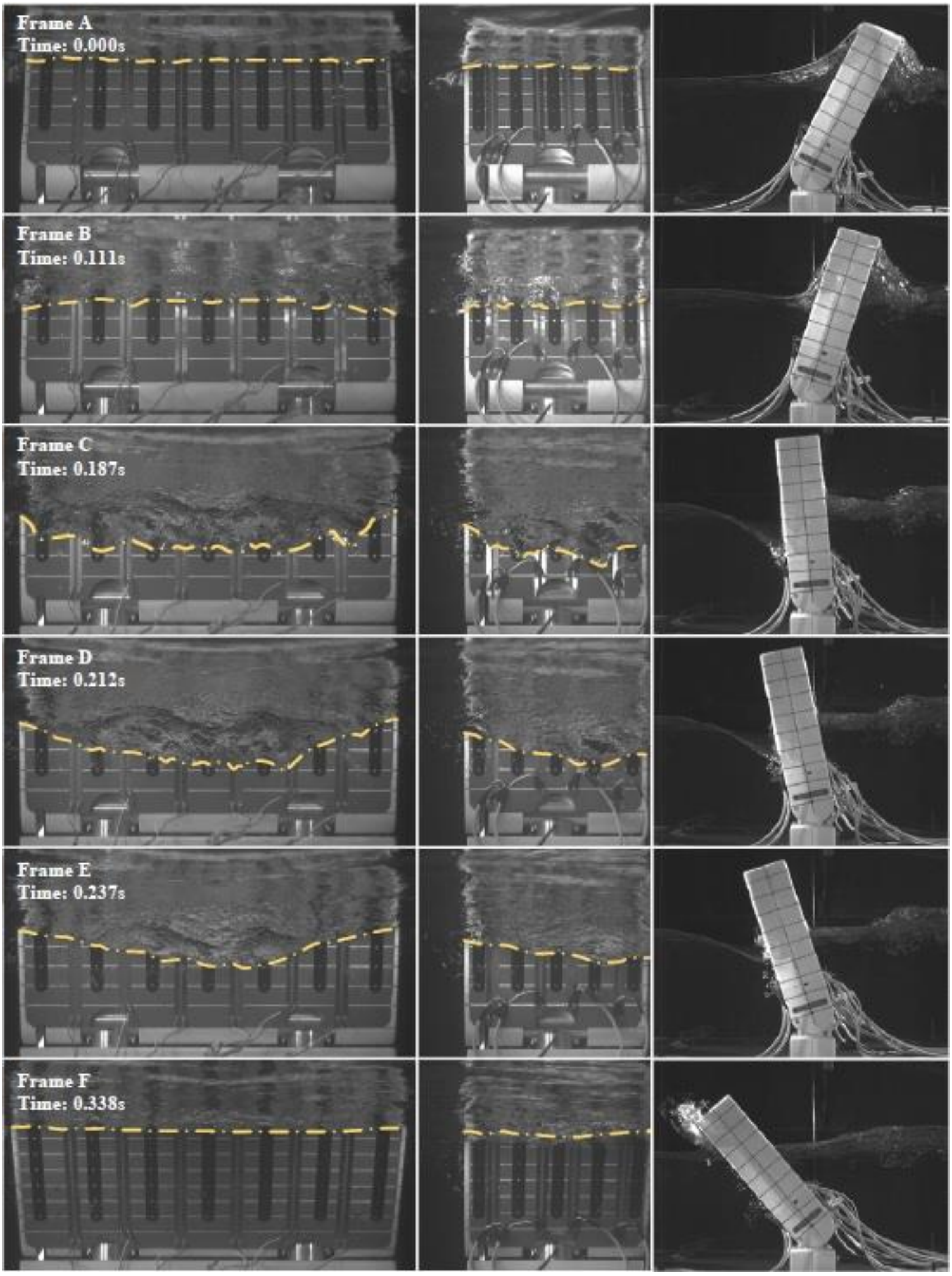


Figure 54. High speed camera images of: (left) pure 3D tests; (centre) 2½D tests where the solid wall is located on the right-hand side of the flap. Both series of images show the front/seaward face of the flap and the surface elevation level on the flap structure is highlighted with the yellow line. (right) side view of the 2½D tests taken through the glass wall of the QUB wave tank.

2014 - 2016 – Ref. [G10], [G11], [G12], [G13] – Assessing the structural response of a flap model and its effect on load measurements using experimental and numerical techniques.

Vibrational response and load transfer of a structure is a topic which is closely linked to the impulsive wave slam event discussed in this section. This issue has significant implications not only in the design of a full-scale structure but also in smaller scale experimental models and in the development of numerical tools.

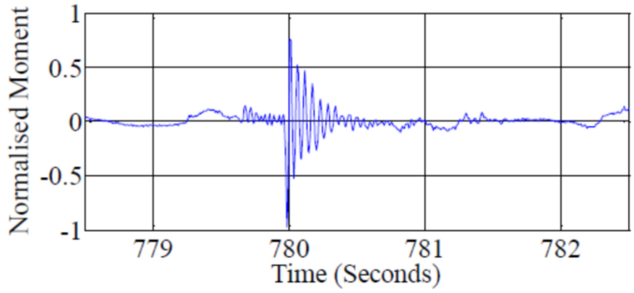


Figure 55. Vibration response (or 'ringing') of a flap model to an impulsive load event.

During small scale wave tank testing of a flap-type device, APL uncovered an issue in the measurement of foundation load data during the slamming events. This is the high-frequency vibrational response of the experimental model and associated instrumentation (e.g. load cells) itself, following the impact. See Figure 55 for an example of the vibrational response or 'ringing' signal recorded by a load cell at the foundations of the scale flap model after an impact event. The ringing characteristics will be unique to the design of the scale model itself and are not necessarily reflective of the equivalent full-scale structure itself. Amplification of the loads can also occur as it is transferred through the structure from the point of impact. Given the fact that the bulk of design load data comes from experimental testing, undesired features such as ringing and load amplification reduce confidence in the values derived and can directly affect the development of a WEC's structural design.

The experimental tests reported by [G10] on a 40th scale flap give an excellent overview of the issue at hand. The modal response of the experimental set up is analysed in detail in several degrees of freedom and the influence the surrounding fluid has on a structures response is quantified. The key parts of the flap model and relevant instrumentation which influence the modal response are identified.

A fully coupled hydrodynamic-FEA numerical model is developed and presented in [G11], [G12] and [G13]. The open source software *NEMOH* and *Code_Aster* are used to develop the model. The tool shows how the effect of the surrounding fluid (i.e. fluid added mass effects) can be incorporated into structural FEA calculations. Numerical results are validated using experimental data and highlight the importance of accounting for added mass in the structural design.

2012 - 2013 – Ref. [G14], [G15], [G16] – Internal APL summary and methodology reports of how slam load data can be applied in the practical design of a real full-scale flap structure.

Although written prior to the detailed research (listed previous) was conducted, these reports provide a very pragmatic approach of how load data can be interpreted and utilised in the engineering design of a real full-scale structure. With such a complex and multifaceted problem, which is investigated in a huge amount of academic detail, it is important to ensure that the knowledge can be applied in practice. These reports give a flavour of the practical constraints and suggest techniques that could be adopted in the design process.

11.3 External Influences on the Research Programme

This research topic encompassed a wide collaboration between APL and many of its partner institutes. Most notably with QUB, UCD, TUHH, HR Wallingford and École Centrale de Marseille.

From APL's perspective, the motivating factor which triggered this research was the need to derive appropriate slam load design cases for the Oyster801 WEC, both in terms of the flap structure and the foundation design. It was proposed that this flap structure was to be fabricated from a Fibre Reinforced Plastic (FRP) material and mounted on a single monopile foundation. Thus, localised impact pressures on the flap, structural vibrations and load transfer through the foundations were of key concern. Such engineering assumptions influenced the direction of some of the research conducted.

11.4 Results and Conclusions

1. **A slam load event triggers 2 key processes which can significantly influence the design of a WEC: (1) localised fluid impact pressures on the structure; (2) the modal/vibrational response and transfer of the impulsive load through the structure. Decoupling these processes can be crucial in order to gain insights into the complex mechanisms involved.**

   Although inherently coupled, each of these processes involves significantly different mechanisms which combine to create the complete event. As such, different research and analysis techniques are usually required in order to investigate each aspect.

   For example, heavily instrumented experimental models are required to accurately determine the localised pressure impact effect on a structure (see point 2 below). Such instrumentation is usually structurally invasive and so influences the modal response of the model itself. Conversely, in order to ascertain the structural response characteristics of a model, a simple structure as possible is often required. Thus, from the outset of a research programme it can often be more effective to design independent models and experiments which targeted each process separately, rather than striving to try and achieve a 'one model fits all' approach.

   A similar ethos of process decoupling can also be employed in the specification of design loads. A WEC operating in waves will experience 'pulsating' loads which are typically of the same time scale order as the wave and/or device oscillatory period. 'Impulsive' loads are those short duration load spikes which occur at an impact event. They may encompass the vibrational response characteristics also. [G14] outlines a practical technique of decoupling these two signals with a high/low pass filter. If derived from small scale tank tests, pulsating loads can be scaled with confidence according to Froude scaling. However, depending on the nature and processes involved in the impulsive loads, a different approach to scaling may have to be adopted. This segregation of loading conditions also permits a particular effect to be investigated in isolation without being 'contaminated' by the other. This leads to richer insights into the processes involved. Once both are appropriately scaled and characterised they can then be recombined to derive the full-scale load condition used in design. APL employed this technique in their engineering designs procedures for the slam load event.

2. **Slamming on the flap is a highly complex and multi-faceted phenomenon. Experimentally, it requires the simultaneous measurement of a multitude of different variables in high-quality wave tank tests in order to fully identify and interpret the mechanisms at play.**

   Through an iterative research process, it was found that an increasing amount of instrumentation was required and incorporated into APL's experimental wave tank models. Ultimately it was concluded that as a minimum, the following experimental measurements and techniques are required to extract the key insights and understanding of the processes at play in a wave slam event:

   - High spatial resolution pressure measurements across the face of the flap. (Ideally, a 'continuous' pressure mat solution would be developed)
   - Flap rotation/motion measurements
   - Direct flap acceleration and vibration measurements (e.g. accelerometers)
   - Instantaneous wetted surface around the entire structure (e.g. non-invasive conductivity stripes built into the flap)
   - Foundation loads measurements (e.g. load cells which capture the global response of the structure to the impact event)
   - High-quality, high-speed images of the slam event.
   - Triggering of very high data acquisition sampling rates (kHz) during the slam event.

   Such levels of instrumentation were installed with high success in the experiments presented by [G8].

3. **High-quality, high-speed images of the experimental wave tank tests are one of the most valuable data sources in the investigation of slamming events.**

   Throughout the research programme, visualisation has been found to be the single most beneficial tool to record information experimentally. Ideally, this would be carried out from several viewpoints simultaneously. Quality imagery can quickly identify many of the fundamental mechanisms at play and help with the interpretation and verification of data from other instrumentation. Non-invasive, it can be the catalyst or key to unlocking an understanding of a complex fluid process.

   Although largely providing qualitative insights, sophisticated image processing techniques enables some quantitative measure to be obtained also. An example of the is the instantaneous wetted surface on the flap and calculation of the jet-root velocity determined by [G6].

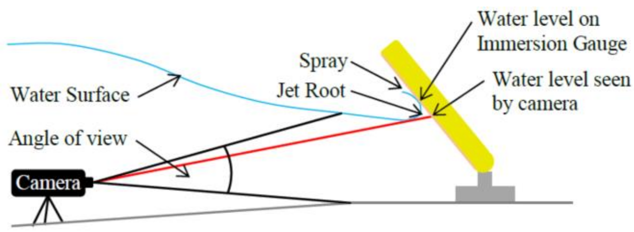


Figure 56. Example of a key view point to image during a wave slam event on a flap

4. Qualitative understanding and visualisation of the slam event can be obtained much more readily with 2D experimental tests. However, the quantitative assessment of key variables, such as impact pressure, was found to be significantly underestimated.

The simplification of the slam problem to what is essential a 2D problem (i.e. a flap which covers the entire width of a wave flume) enables high-quality images and a qualitative understanding to be obtained much more readily. However, it is well known in the industry and has been demonstrated here again, that the quantitative behaviour of a device in 3D is significantly different than in 2D. This is described in detail by [G9] which shows that the characteristic of the impact pressures on the face of the flap are significantly different in 2D compared to 3D and that the magnitude is underestimated by a factor of two. 2D investigations are however a good validation step in the development process of sophisticated numerical CFD models.

5. CFD techniques have been shown to be very effective tools in the investigation of a highly complex slam loading event

It has been demonstrated by [G1], [G2] and [G3] that CFD techniques, such as a VOF method and SPH, can accurately model and aid in the understanding of a complex wave slam event. One of the key insights numerical techniques provide (with no practically achievable counterpart in 3D experiments) is detailed measurements of the flow characteristics, i.e. velocity, pressure, vorticity, turbulence etc. The highly non-linear slam event falls well within the remit of CFD techniques and the short duration of the process is also compatible with the high computational effort required from these techniques.

6. It is essential that in a WEC design, the added mass effects of the surrounding fluid are correctly incorporated into any structural FEA computations.

FEA methods are well established and are commonly used in most structural analysis research. However, these techniques commonly model the structure in air. Clearly, for WECs this is an erroneous simplification. Historically, the influence of the surrounding fluid has not been incorporated correctly, or at all, in FEA techniques. The pioneering research conducted by [G11], [G12] and [G13] presents a method of numerically coupling hydrodynamic and FEA calculations to overcome this deficiency. The tool can perform modal analysis on a structure partially or wholly immersed in a fluid and determine the modes of vibration and associated eigenfrequencies. Preliminary numerical results have been validated by experimental tests and show that it is an effective way of accounting for the effects of fluid added mass. To put the importance of this in context, the experimental test results presented in [G10] shows that the difference in modal frequency between a dry and fully submerged flap can be of the order of 69%. In addition, when submersed in fluid, the primary mode of vibration can be altered. Both these effects can have a significant influence on the design of a structure.

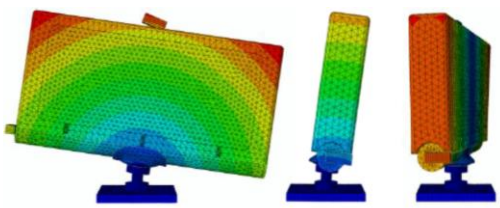


Figure 57. Example of FEA modelling of a flap.

11.5 Outcome of the Research

Preliminary results from the research programme fed into the FEED of the Oyster801 concept. However, from 2013 onward the company focused more of its engineering effort retrospectively re-engineering subsystems on the on Oyster800 prototype, installed at EMEC. As such the development of the Oyster801 design and associated research, such as the investigations into slam loads, progressed on a slower time scale and was mostly lead by the company's academic partners QUB and UCD. APL ceased trading before the true value and insights of this research came to fruition.

11.6 References

[G1]. Wei, Y., *et al*, (2016), "Wave Interaction with an Oscillating Wave Surge Converter. Part II: Slamming", *Ocean Engineering, Vol. 113, p 319 – 334.*

[G2]. Henry, A., *et al*, (2013), "The Characteristics of Wave Impacts on an Oscillating Wave Surge Converter", *Proc. 23rd Intl. Offshore & Polar Eng. Conf., (ISOPE), Anchorage, Alaska*.

[G3]. Henry, A., *et al*, (2014), "The Characteristics of Wave Impacts on an Oscillating Wave Surge Converter", *Journal of Ocean and Wind Energy, Vol. 1, No. 2, pp. 101-110.*

[G4]. Henry, A., *et al*. (2014), "A Two Dimensional Experimental Investigation of Slamming of an Oscillating Wave Surge Converter", *Proc. 24th Intl. Offshore & Polar Eng. Conf., (ISOPE), Busan, Korea.*

[G5]. Henry, A., *et al*, (2014) "2014 ISOPE-TPC-0969 - A Two Dimensional Investigation of Slamming of an Oscillating Wave Surge Converter - A1.pptx", *Presentation for ISOPE conference as referenced in [G4]*.

[G6]. Lebrun, V., (2014), "The Slamming of an Oscillating Wave Surge Converter", *Research Thesis, UCD & Ecole Polytechnique*.

[G7]. Henry, A., *et al*, (2015), "The Vertical Distribution and Evolution of Slam Pressure on an Oscillating Wave Surge Converter", *Proc. 34th Intl. Conf. Ocean, Offshore & Artic Eng. (OMAE), St. John's, Newfoundland, Canada*.

[G8]. Lamont-Kane, P., *et al*, (2015), "Investigating Extreme Loads on an Oscillating Wave Surge Converter", *11th European Wave & Tidal Energy Conference (EWTEC), Nantes, France*.

[G9]. McKinley, A., *et al*, (2016), "Preliminary Development of a Pseudo-3D Testing Technique for the Prediction of Extreme Loads on an Oscillating Wave Surge Converter", *3rd Asian Wave and Tidal Energy Conference (AWTEC), Singapore*.

[G10]. McKinley, A., *et al*, (2014), "The Structural Response of an Oscillating Wave Surge Converter to Wave Slamming", *Intl. Conf. on Offshore Renewable Energy (ASRENet), Glasgow, Scotland.*

[G11]. Windt, C., *et al*, (2014), "Development and Validation of a Finite Element Analysis Procedure for Numerical Vibration Analysis of the Oscillating Wave Surge Converter Oyster", *1st Intl. Conf. on Renewable Energies Offshore (RENEW), Lisbon, Portugal.*

[G12]. Windt, C., (2014), "Numerical Studies on the Structural Behaviour of an Oscillating Wave Surge Converter", *Bachelor Thesis, TUHH – QUB – APL*.

[G13]. Schmitt, P., et al, (2016), "Development and Validation of a procedure for numerical vibration analysis of an oscillating wave surge converter", *European Journal of Mechanics B/Fluids, 58, pp 9 -19*.

[G14]. Hancock, J., (2012), "OY801-TN-0025 - Proposed Method for Determining Slam Loads on Oyster - A1.docx", *Internal Report, APL*.

[G15]. Hancock, J., (2012), “OY801-TN-0010 - Proposal for incorporating slam loads into 801 flap design - B1.pdf”, *Internal Report, APL*

[G16]. Henry, A., (2013), “130301 Recent Work on Wave Impact Pressures APL-RD FDR 04-REP-0130 - A3.docx”, Internal Report, APL.

12 (H) A Fabric Flap WEC Concept

12.1 Research Hypothesis or Motivation

The vast majority of APL's research and engineering efforts was on bringing the design of a large, structurally rigid flap-type WEC to reality. However, diversifying the technical portfolio of device concepts and exploring radically new design spaces was also a key objective. Exploratory research can often unlock new Intellectual Property opportunities and novel ways to achieve a more cost-effect technology solution. One such research programme initiated by APL was the potential use of a fabric or flexible material for the main body of the flap-type device. An example of one such possible 'fabric flap' design is illustrated in Figure 58 where the fabric (purple) is attached to independent vertical posts, each with their own PTO mechanism (e.g. hydraulic cylinder(s)) and foundation (e.g. a pile).

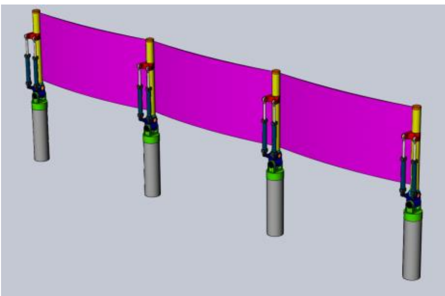


Figure 58. A fabric flap WEC concept

Such a significant departure from a rigid flap design could present several opportunities, but also new challenges. Prior to any research being conducted by APL the postulated benefits included:

- Greater WEC density per km of coastline. A continuous curtain type design covers more of the coastline without suffering from the energy capture limits of a 2D terminator device, as each vertical post/PTO member can move quasi-independently for its neighbour.
- The cost of material, associated handling and installation overheads could be reduced compared to an equivalently large rigid flap(s).
- Losses from wave directionality and wave short-crestedness could be reduced.
- Design is more adaptable to the meandering depth contour along the nearshore bathymetry.
- Potential for natural power smoothing across the device due to the slight out-of-phase motion of independently moving posts. (fully dependent on PTO system design)

Early technical challenges which were expected with this concept include:

- The flexing and possible billowing of the fabric material represents energy loss in the prime mover.
- Achieving adequate restoring torque (pitch stiffness) may be difficult without designing in some additional buoyancy elements and/or the use of elastomers (see Section 0 for more detail).
- Tension and snatch loading in the fabric material, especially in larger wave conditions.
- Degradation of the fabric material under UV exposure, biofouling and colonisation.
- Abrasion, material interface and connections with other parts of the WEC.

12.2 Year and Research Activity

- **2010 – Ref. [H1] – Fabric WEC flap concept pre-feasibility study.**

  A pre-feasibility study of the fabric flap WEC concept. Outlines the basic operational principles and motivations for exploring such a concept. Provides a very high-level design of a possible WEC configuration (Figure 58), basic risk assessment preliminary literature review of fabric material studies and source of information.

- **2011 – Ref. [H2] – Fabric material feasibility study.**

  A desktop material feasibility study into the use of flexible and/or fabric material to replace the main body of a large 26m wide flap-type device (i.e. the dimensions of Oyster800). The study explored a vast range of possible materials from polyester, to glass-fibre to high performance rubber and other synthetic weaves. Consideration was given to: flap geometry and structural configuration; wave loading; bio-resistance and the marine environment; temperature and UV exposure; cabling and tear resistance; high-level cost estimates were attempted on some sub-components but an overall concept costing was not achieved. No definitive design conclusions were reached but the report presents a thorough review of the challenges that must be considered in the use of fabric material for this purpose.

- **2011 – Ref. [H3] - [H10] – Experimental wave tank testing of a 40th scale fabric flap model.**

  Experimental wave tank tests were conducted at the wave tank facility at Queens University Belfast (QUB) on a 40th scale fabric flap model with dimensions similar to that of the Oyster800 device (i.e. 26m wide, 12m tall and operating in 13.4m water depth).

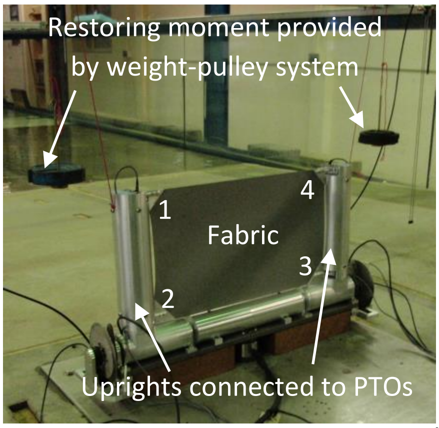
  

  Figure 59. Fabric flap model used in 40th scale wave tank tests

  The model, as shown in Figure 59, consists of two vertical upright posts between which the fabric material is attached. Each upright/post has a PTO damper connected to it and the model was constrained to operate in pitch only. As designed, the model was actually negatively buoyant. So in order to facilitate a comparison of this concept to a rigid buoyant flap, a restoring moment was applied to each upright/post through a weight-pulley system suspended above flap, as shown in Figure 59. It was felt that this artificial mechanism was adequate for the preliminary concept tests as it avoided trying to integrate buoyancy elements into the fabric material or alternatively trying to introduce novel elastomer material to the hinge point of the device. Secondly, a key driver of these tests was to directly compare the performance of a fabric flap with an equivalent structurally rigid flap and a fully buoyant flap. The weight-pulley system enabled quick and easy adjustments to be made to the magnitude of the restoring moment to match that of the reference buoyant flap, thus isolating only the effect of the fabric material itself.

  A 6 month experimental research programme was designed and dedicated to exploring the power capture and tension load characteristics of this WEC concept. The power capture performance was determined from 7 irregular sea states, representative of the nearshore EMEC site in Orkney. Tension forces were measured at the 4 corners of the fabric material where it attached to the vertical upright posts, indicated with the labels 1,2,3,4 in Figure 59. Refinements were made to the experimental test over the course of the programme to improve the quality of the results obtained, such as how the load/tension sensors were mounted and how the fabric material was attached to the uprights etc.

Several different flap configurations and scenarios were tested during the programme and compared against each other to gain insights into the behaviour and characteristics of the device. These were:

- OY2a Aluminium – Baseline Oyster800 device (e.g. 40th scale equivalent of Figure 34) used as a performance reference point to an existing technology.
- Rigid Flap – Identical test rig as the fabric flap (i.e. Figure 59) but the fabric material is replaced by a rigid piece of PVC sheet. Direct reference to isolate the effect of the flexible material and minimise any other discrepancies induced from different experimental test configurations.
- Original Fabric Flap – The first iteration design where a non-elastic fabric material (boat cover) was attached to the upright only at the 4 corners (as in Figure 59).
- Taut Fabric Flap – Second iteration design where side stiffeners were attached to the fabric material to improve the vertical tautness of the material. See Figure 60 for a comparison of the edge of the fabric material on the 'Original Fabric Flap' and with the side stiffeners. Note, connection to the uprights is still only at the top and bottom corners.
- Unlocked Flap – Configurations where the two upright posts can move independent of each other.
- Locked Flap – Configuration where the two upright posts are connected together with a thin rigid bar across the top. Thus, they no longer move independently of each other.
- Neoprene Flap - An elastic neoprene material was used as the fabric and the effect material tautness (in the horizontal direction) has on the device performance was explored.

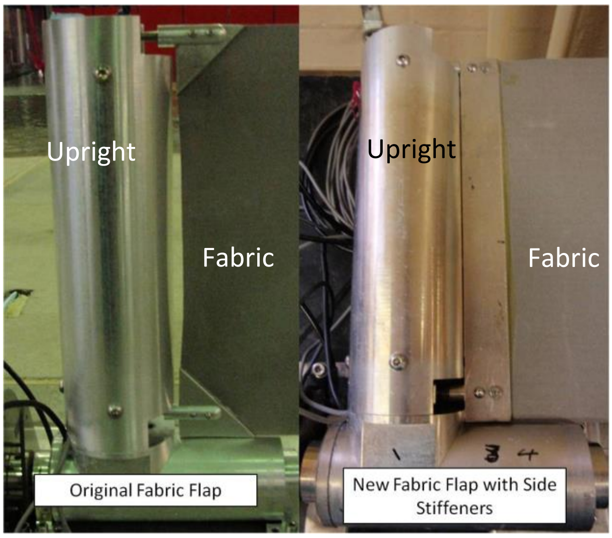


Figure 60. Comparison of the edge configuration of the fabric material for the 'Original Fabric Flap' (left) and the 'Taut Fabric Flap' (right) which has a vertical side stiffener.

As well as the data acquired from the instrumentation, a large amount of video was also recorded of the fabric flap wave tank tests. This may help with a qualitative understanding of the typical behaviour of this concept and aid in the interpretation of the quantitative results.

12.3 External Influences on the Research Programme

This exploratory research conducted was purely under APL's control and there was no significant external influence on the programme.

12.4 Results and Conclusions

1. **The tautness of the fabric material is critical to the power capture performance of the device. A loose fabric flap captures circa 25% less power than a taut fabric configuration.**

   The influence material tautness has on the performance of the device is reported in [H6], [H7] and summarised in the technical presentation [H5]. Two different configurations were used to examine the effect. The first was using an inelastic fabric material of two different sizes. The second used an elastic neoprene material which was stretched to 4 different levels of tautness between the two upright posts. In all cases the two posts were rigidly locked together so it was purely the effect of material tautness that was examined.

   In both cases the 'loose' flap was found to only capture circa 75% of the power of the taut flap. The largest power gains were achieved from an initial tightening of the material. Beyond this, the performance gains were not as significant. This result indicates that there is possibly a critical tautness above which the performance will not be enhanced.

   Significant power losses (between the taut and loose flap) of circa 70% were recorded in smaller sea states with less dramatic losses of circa 15% in large seas. Losses can be closely correlated to the Span-to-Dip ratio of the material, see Figure 61. If the span:dip ratio is low (i.e. a loose flap) the wave excitation force billows the material but does not necessarily cause any rotation of the flap (especially in smaller waves). Conversely, if the span:dip ratio is larger, less energy is consumed by billowing the material and the flap will rotate more, thus increasing the power capture.

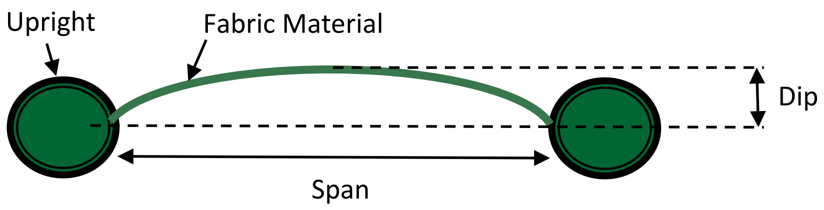


Figure 61. Plan view of the fabric flap

   During the test programme, span:dip ratios of between 4 and 7 and between 24 and 32 were tested for the elastic and inelastic material respectively. In both cases the highest ratio (i.e. most taut) performed the best and the inelastic material significantly out-performed the elastic material. From a practical material perspective, typical span:dip ratios are between 8 and 12 for tensile fabrics (see [H2]) and so achieving the desired level of tautness to improve power capture may not be possible in practice.

2. **Gaps between the edge of the fabric and support structure elements allows fluid to 'pass-through' the flap, resulting in power losses**

   This effect was reported in [H3] on the 'Original Fabric Flap' iteration using an inelastic fabric material. Figure 60 (left) shows a gap at the edge of the material which promotes vertical billowing and results in a significant energy loss. In fact, it was shown that if this gap is closed and the vertical tautness increased with the use of side stiffeners, the power capture increased by circa 45%.

   In a similar manner, [H6] reported that, when using an elastic neoprene material which is stretched taut between the vertical uprights, a scalloped shaped gap developed along the bottom hinge line (and top of the flap) due to material distortion. This again creates significant energy losses.

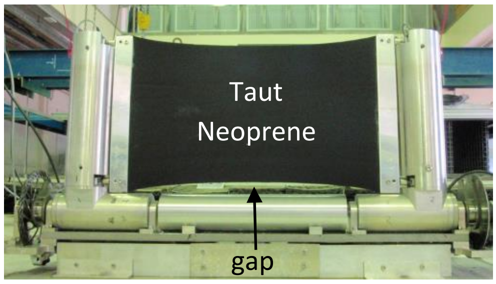


Figure 62. Front view of a neoprene flap

3. **A loosely-taut inelastic fabric flap with independent rotation uprights (unlocked) captures less than 55% of the power of a rigid equivalent flap. A highly-taut inelastic fabric flap with independent rotation uprights (unlocked) captures less than 80% of the power of a rigid equivalent flap. A highly-taut inelastic fabric flap with rigidly locked uprights captures less than 90% of the power of a rigid equivalent flap and was found to be the best fabric flap configuration tested.**

   Figure 63 shows a comparison of the average annual mechanical power captured from a few different fabric flap configurations. The performance of a rigid equivalent flap (i.e. the fabric is replaced by a stiff PVC sheet in the experimental tests) and that of the Oyster800 device (titled "OY 2a Aluminium") is also shown for comparison.

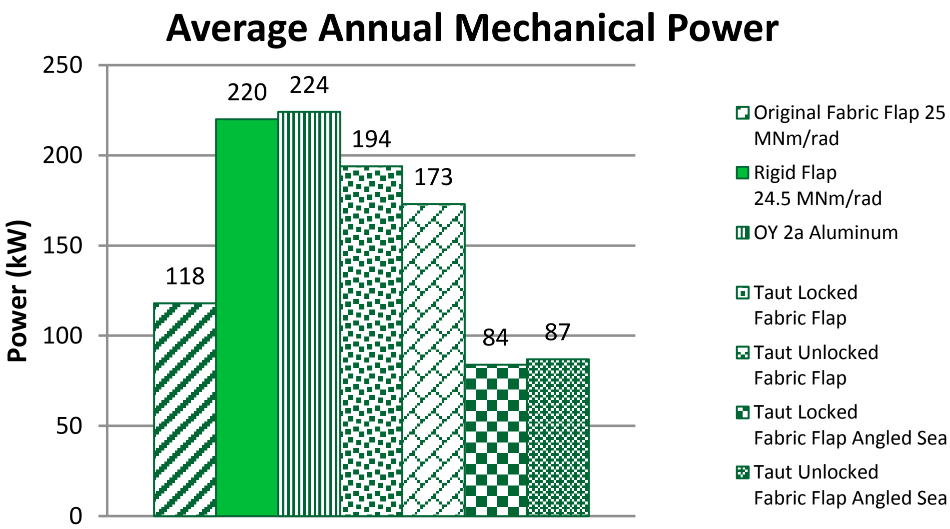


Figure 63. Annual average power capture of various rigid and fabric flaps. The 'Original Fabric Flap' represents a loosely-taut fabric with vertical gaps exposed at the edge due to billowing. The 'Taut Locked' flap has vertical fabric stiffeners which reduces billowing and the upright posts are rigidly connected together. The 'Taut Unlock' flap employs the material side stiffeners but the upright posts are able to move independently from each other.

The results clearly show that a fabric flap concept results in a significant reduction in power capture, when compared to an equivalent rigid flap. Any performance improvements on the fabric flap concept transpire by stiffening the flap (i.e. highly taut material and rigidly connecting the uprights), essentially merging it towards the characteristics of a rigid structure. The lower performance of a fabric flap, compared to a rigid flap, comes from a poorer performance in the smaller and most commonly occurring sea state. This again is due to the dominant effect of billowing in the material rather than rotational movement of the vertical posts which are linked to the PTO system.

Tests were also conducted in sea states incident at 45^{o} to the fabric flap (which is very extreme for a nearshore device). As expected, power was significantly reduced when compared to head-on seas but there was negligible difference in the overall power if the vertical posts were lock or unlocked. However, an observation was made in the data that when the uprights were unlocked (free to move independent of each other) the upright closest the land was more energetic and captured more power than the seaward post. This possibly eludes to a 'build-up' of energy as a wave propagates down along the flexible structure. If the fabric structure was much longer (i.e. a large curtain-type concept) some of the power loss in off-angles seas may be recovered via this mechanism.

It should be noted too that all performance test results were based on the device with a large (25MNm/rad) artificially applied restoring moment (pitch stiffness) induced during the experimental tests from a weight-pulley system. Such a mechanism has no direct counterpart in reality. The integration of such high levels of buoyancy into a fabric flap concept are also challenging and unlikely. Thus, the tests results present an overly optimistic view of the power capture performance of this device concept.

4. **Tension snatch-loads are larger in an inelastic loosely-taut fabric (>22MN) but the average tension is larger in a highly-taut inelastic fabric flap. Both loads increase with increasing significant wave height.**

Several iterations of experimental tests were conducted to assess the tension loading in the fabric material. Preliminary test reports are [H9] and [H10] but the most conclusive results are contained in [H7] and [H5]. As might be envisioned, the test results show that:

- The average tension in the inelastic fabric increases as the PTO damping increases (i.e. the rotational resistance of the flap is larger).
- The average tension in the inelastic fabric increases as the tautness of the fabric increases.
- The average tension in the inelastic fabric increases with significant wave height.
- The largest maximum tension in the inelastic fabric was recorded in a loose flap. This represents snatch loading in the material upon sudden load impact or reversal.
- Maximum tension loads of over 22MN were recorded during the tests and the maximum load consistently occurred on the lower connection points (i.e. closer the hinge line), although no definitive explanation for this was reached.
- The average and maximum loads in an elastic neoprene flap were considerably smaller than the inelastic fabric flap.

12.5 Outcome of the Research

The overall appraisal of this concept is that the significantly reduced power capture ability and engineering challenges associated with large tension and snatch loads would overwhelm any perceived cost or operational benefit that may be introduced with replacement of a rigid flap with a highly flexible material. This was compounded further by discussions given in the material feasibility study ([H2]) which emphasised the highly novel application of existing flexible materials for this use and a lack of appropriate historic data to base early design calculation on. Thus, APL decided that the high engineering effort, risk, cost, and low probability of beneficial returns meant that this concept should not be pursued and was de-prioritised over other company objectives.

However, even though a fabric flap concept was not pursued any further, there were elements of the research programme that were deemed to have potential. The idea of a long, continuous, compliant flap-structure could still offer advantages over a rigid structure. Thus, the research evolved into exploring a modular version of a flap-type WEC which is discussed in detail in Section 13.

12.6 References

[H1]. Steynor, J., (2010), "100831 Fabric Oyster Pre-Feasibility Study -APL-RD.SP.17-REP-0001-A2", *Internal Report, APL.*

[H2]. Currie, N., (2011), "Aquamarine Power Phase 1 Draft Rev 2", *External Report commissioned for APL*.

[H3]. Wright, B., (2011), "110301 Initial Testing of the Fabric Flap - APL-RD.SP.19-REP-0001 - A2", *Internal Report, APL*.

[H4]. Wright, B., (2011), "110401 Fabric Flap Performance Comparison - APL-RD.SP.19-REP-0002 - A1", *Internal Report, APL*.

[H5]. Wright, B., (2011), "*110525 Fabric Flap Final Presentation*", Internal Report, APL.

[H6]. Wright, B., (2011), "110521 Explanation of Neoprene and Fabric Flap April Testing - APL-RD.SP.19-REP-0005 - A1", *Internal Report, APL*.

[H7]. Wright, B., (2011), "110521 Effects of Tautness on Neoprene and Fabric Flaps - APL-RD.SP.19-REP-0006 - A2", *Internal Report, APL*.

[H8]. Wright, B., (2011), "110521 Explanation of Neoprene and Fabric Flap April Testing - APL-RD.SP.19-REP-0005 - A1", *Internal Report, APL*.

[H9]. Wright, B., (2011), "110510 Analysis of Tension in Fabric Flap Testing - APL-RD.SP.19-REP-0004 - A1", *Internal Report, APL*.

[H10]. Wright, B., (2011), "110503 Extended Analysis of Tension in Fabric Flap Testing - APL-RD.SP.19-REP-0003 - A1", *Internal Report, APL*.

13 (I) A Modular Version of a Flap-Type Device

13.1 Research Hypothesis or Motivation

Aquamarine Power successfully designed, installed and operated two full scale WEC prototypes, namely Oyster 1 and Oyster800, at EMEC and completed the FEED and initiated the detailed designed of a third-generation device, Oyster801. Conceptually though, these devices all fell into the same category in the fact they consisted of a single wide (circa 20m-30m) prime mover (the flap) designed to operate in the nearshore region. A wealth of research, engineering and commercial knowledge on such a WEC category is contained within the Aquamarine Power intellectual property. However, the company continually explored ways to expand their technology portfolio, not only with iterative improvements to this core flap concept, but with a potential step-change in technology.

One such step-change alternative which came to the fore was a modular flap-type WEC concept. This device would consist of a discrete number of pitching modules that could move independent from each other, with each one potentially driving its own secondary PTO unit. Alternatively, they could all be connected into a single common PTO system. An example of what such a modular WEC could look like is illustrated in Figure 64, where it is compared against the Oyster800 device.

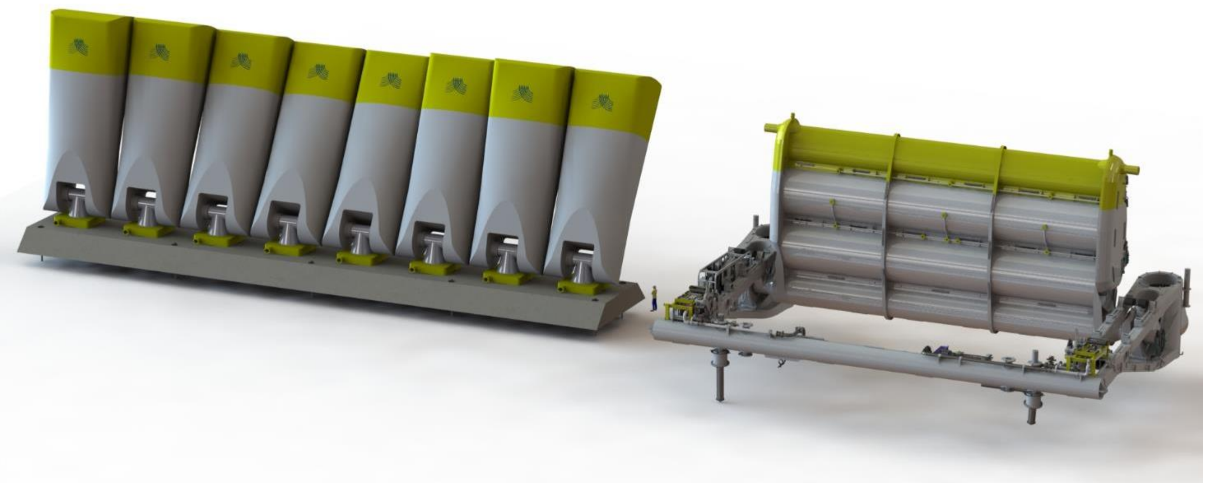


Figure 64. Comparison of a possible modular flap-type WEC concept (left) with the Oyster800 device (right)

There are a host of potential advantages and disadvantages of a modular flap over an equivalent rigid flap, both from a practical engineering perspective and a fundamental operational principle. It was postulated that the expected advantages and disadvantages could be:

<u>Advantages:</u>

- Reduction in the parasitic foundation loads such as Yaw, Roll and Sway, i.e. those degree of freedom that do not contribute to power capture but do cause structural loading and racking.
- Better quality (smoother) power output from the total device due to the naturally out-of-phase motion of the modules.
- Smaller PTO unit capacity required and an opportunity for more advanced control strategies.
- Improved power capture in directional/off-angle waves.
- Possibility of utilising more ‘coastline’ per WEC without encountering the 2D ‘terminator’ hydrodynamic power capture limit.

- Cost reduction in the bulk fabrication of smaller units, transport, installation and offshore handling.

Disadvantages:

- Spacing (even if minimal) may result in a reduction in power capture due to leakage through the flap (thus reducing the incident wave torque).
- Multiple units may increase the complexity (and thus cost) in auxiliary systems such as pipe work, Control and Instrumentation etc.
- Challenging maintenance of a module within the WEC while others are operating. May need to adopt a module-removal strategy which could compromise the other modules etc.

The hydrodynamic response of a modular WEC differs significantly to that of a rigid flap such as Oyster. As such, there were many design space variable that needed to be explored and understood. In this report section, only research that explored the fundamental hydrodynamic characteristics (power capture, loading etc.) of a modular WEC are discussed. However, it should be recognised that Aquamarine Power progressed this technology through to a very detailed concept engineering design. The technology was titled OysterM and the engineering advanced to a Technology Readiness Level (TRL) of 3-4. This knowledge is contained within the Aquamarine Power intellectual property but the details are beyond the scope of this report.

13.2 Year and Research Activity

- **2017 – Ref. [I1] – A 4-year Engineering Doctorate project (IDCORE) dedicated to investigating the hydrodynamic characteristics of a modular flap-type WEC, via high-end 30th scale experimental wave tank testing.**

  This EngD thesis is arguably one of the single most robust sources of information on a modular flap-type WEC concept. It provides a thorough literature review and background to the technology development and explores the hydrodynamic power capture and loading behaviour of the device.

  A sophisticated, high-quality 6-module physical model was designed and built at 30th scale. An exhaustive effort was put into the design and precision fabrication of the model and a controllable PTO damper system suitable for small scale testing. The design and costings are well documented in this thesis and may be of interest to others embarking on physical testing.

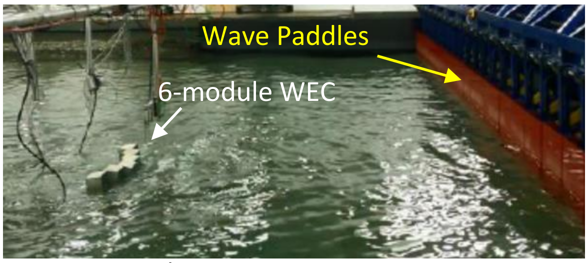


Figure 65. 30th scale 6-module WEC operating in the wave tank facility in Portaferry, NI.

  Experimental tested were conducted at both of Queen's University Belfast wave tank facilities, located in Belfast City and Portaferry, Northern Ireland. Tests were conducted in a variety of regular and irregular wave conditions, incident both head-on and off-angle to the device. The power capture and loading (both extreme and fatigue) characteristics were compared to an equivalent rigid flap. Rich insights into the behaviour of this type of device were established and provide an excellent foundation of knowledge on this WEC concept.

2013 – Ref. [I2] – A literature review study of research and applications of modular flap-type structures in wave environments.

Aquamarine Power recognised that modular flap structures operating in a wave environment was not a novel concept. As such, prior to commencing any significant research and to avoid possible repetition, they commissioned an external study which reviewed the state-of-the-art of the scientific progress of flap structures in waves. The review brought to light two key bodies of research.

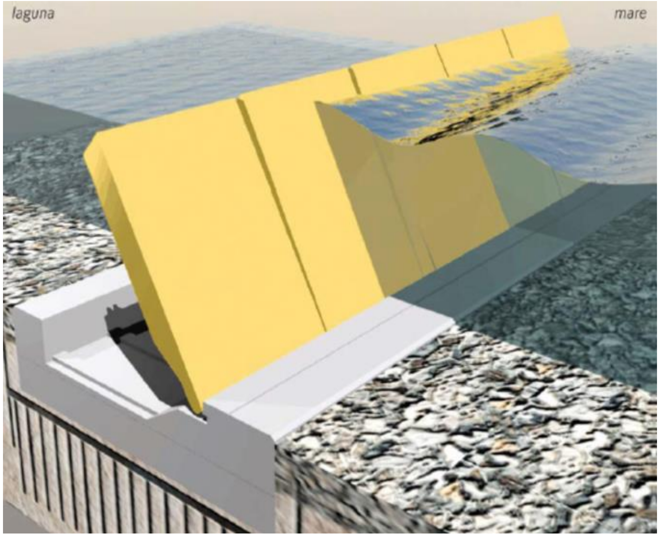


Figure 66. Illustration of the Venice Gates

The most significant of these is the extensive (>30 years' worth) theoretical and experimental research into the application of a coastal protection barrier system to protect the Venice Lagoon from flooding, better known as the 'Venice Gates'. This eight billion-euro project comprises 78 three-hundred tonne gates of typical dimensions 20m x 30m x 5m spanning a total of 1.6km. A wealth of engineering and academic knowledge has come from the research behind this project.

The second body of work identified to be relevant for modular WEC research is the analytical techniques developed by researchers at UCD for a finite (or infinite) array of flap-type WECs. Within this mathematical framework, the model could be used to investigate any configuration of multiple flaps and thus provides a platform to explore the modular WEC concept.

2013 – Ref. [I3], [I4] – Preliminary 40th scale experimental wave tank tests on modular flap-type WEC concepts.

As a first exploration of the behaviour of a modular flap-type WEC, preliminary wave tank tests were conducted by Aquamarine Power at the wave tank facility in Queens University Belfast. These were designed to give a high-level, qualitative view of how such a device behaves in the typical wave climate a nearshore WEC would operate in. A large amount of video and images were taken during the tests and insights into the device response in ocean waves observed. Figure 67 shows an image from one of the wave tank tests comparing the behaviour of a modular flap against a rigid flap in the same head-on incident wave.

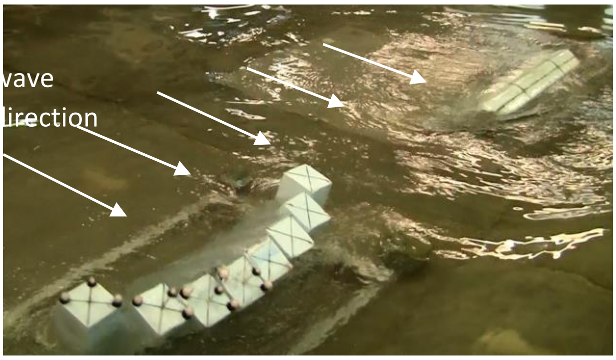


Figure 67. Comparison of an 8-module WEC (left) along-side a rigid flap of comparable width.

- **2014, 2015, 2017 – Ref. [I7], [I8], [I9] – A series of published conference and journal papers reporting the experimental testing of a 30th scale modular flap concept.**

  This series of papers was published by the same author as the IDCORE project. The research presented overlaps with that reported in the IDCORE thesis [I1]. However, the published papers referenced here segment the topics investigated and may make the specific topics more accessible to the reader than navigation through a full thesis such as [I1]. Often a slightly different narrative is given too in each paper which may elaborate each topic in a different way. The topics are categories as follows:

  - [I7] – Assessment of the fatigue and extreme loads on a 6-module flap-type WEC
  - [I8] – Design of an experimental model and the methodology of how to assess the power capture of a modular flap-type device.
  - [I9] – Results of the power capture performance of a 6-module flap-type device and comparison to an equivalent width rigid flap.

- **2015 – Ref. [I10] – An extensive parameter-space analysis of how the geometric variables of a modular flap affect its power capture characteristics.**

  As part of Aquamarine Power's OysterM project, numerical hydrodynamic modelling techniques and experimental tests were used to examine the effect key geometric and PTO features have on the power capture of a modular flap. The key geometric parameters considered along with every permutation/combination of each were as follows:

  - Module width: 3m, 5.8m, 9m, 12m
  - Spacing between modules: 0m, 0.2m, 0.5m, 1m, 2m, 4m, 6m
  - Number of modules in a WEC: 1 to 8 (up to 12 in the case of the 5.8m wide modules)
  - A single large rigid flap of equivalent width of all possible combinations listed above.

  Within this parameter space, over 250 different WEC configurations exist. Due to the large number of configurations, numerical modelling results were used most extensively but some experimental wave tank test results are also presented. In some cases, a full time-domain hydrodynamic model was implemented, various PTO damping strategies on each module investigated and the power capture calculated directly. In other cases, only the incident wave torque induced on the WEC was used as a pseudo-metric of power capture (as flap-type WECs are predominately wave force driven, see Section 0). Although a direct power number wasn't returned in these cases, a relative comparison between different WEC configurations was achieved and insights drawn.

13.3 External Influences on the Research Programme

From the inception of the modular flap concept within Aquamarine Power (circa 2013), the majority of the research was led by a research student of the IDCORE programme. This was co-supervised by Aquamarine Power and Queens University Belfast, along with the lead academic consortium partners of the IDCORE programme. This was designed as a 4-year research programme. Historical literature review of modular structures and the development of mathematical and analytical models were led by UCD, one of Aquamarine Power's academic partners.

During the early research (2013/2014), Aquamarine Power staff focused most of their efforts on the operation and engineering improvements to the Oyster800 prototype installed at EMEC. Thus, the majority of staff didn't become involved until the initiation of the OysterM project in 2015.

13.4 Results and Conclusions

1. **The dynamic response of a modular flap to wave action is significantly different to an equivalent width rigid device. Multiple natural frequency points exist and transverse resonances (along the face of the device) can induce complex motions and can cause adjacent modules to move in different directions to each other.**

This phenomenon was first discovered through the research and development of the Venice Gate project. A rich variety of complex dynamic motions were first observed in experimental wave tank tests, with period doubling behaviour and out of phase motion of adjacent modules/gates observed, see Figure 68 for example. Extensive mathematical and analytical research later predicted this behaviour, confirming its true existence. A good summary of this early research on the Venice Gate project is given by [I2].

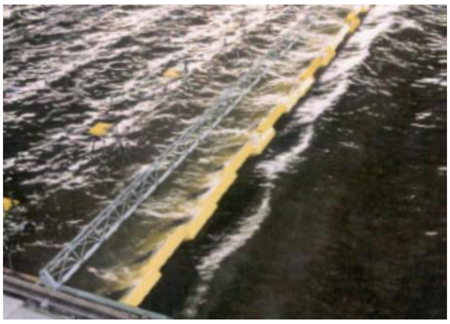


Figure 68. Adjacent Out-of-phase motion observed in the Venice Gate experiments

Since this pioneering research, this complex natural response has been observed and reported from the experimental tests of Aquamarine Power's modular WEC concept [I1], [I4], [I10]. It has also been predicted from the analytical work of [I6] and [I5], which modelled different configurations of modular flap-type WECs. Figure 69 shows a plan-view image of the three natural response modes of a 6-module WEC, as predicted by the analytical work of [I6]. Each circle represents an individual flap module and the arrow shows the direction of wave propagation. This illustrates the various modes of motion that can be excited by different incident wave frequencies. In this case, the wave periods which induce these natural modes are approximately 9s, 11s and 17s for profiles (a), (b) and (c) respectively. The dynamic response becomes increasingly complex as the number of modules in the WEC increases, but also too in irregular sea states where a broad range of wave frequencies excite the device. Often, several different modes of operation can be observed within the same sea state. An example of this was reported in [I4] and is illustrated here in Figure 70.

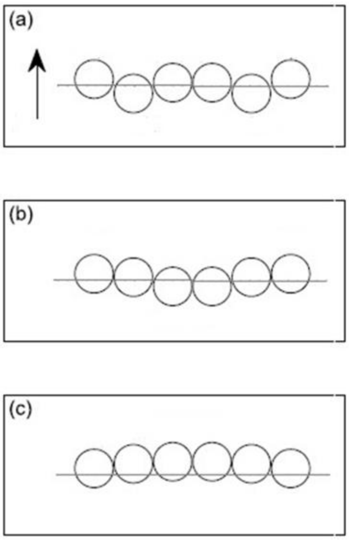


Figure 69. Three response modes of a 6-module flap

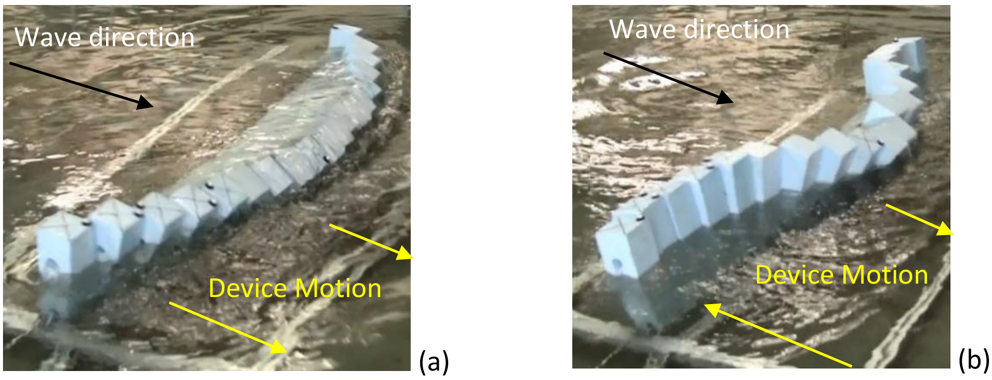


Figure 70. Example of the different device motions of a 19 module WEC in the same irregular sea state

2. **In head-on waves, the power capture ability of a modular flap (with a simple, constant PTO damping applied evenly to every module) is only marginally less than an equivalent width rigid flap. However, the power smoothness/quality from a modular WEC is better.**

Extensive experimental wave tank tests, reported in [I9] and [I1] on a 6-module flap (with a minimal spacing between each module), show that the power capture is only marginally lower than that for an equivalent width rigid flap. Figure 71 shows the percentage difference in capture factor (or capture width ratio) between the modular and rigid flap, plotted against the monochromatic incident wave period. A negative value means that the rigid flap performs better. (The error bars shown describe the uncertainty in the experimental tests and data analysis techniques). As might be expected, the modular flap performs better in short period waves as the wide rigid flap suffers more from a 2D terminator-type behaviour. Irregular sea state tests reported in [I1] show that in head-on seas, the modular flap captures circa 4% less power than a rigid flap in the typical wave conditions expected at a deployment site.

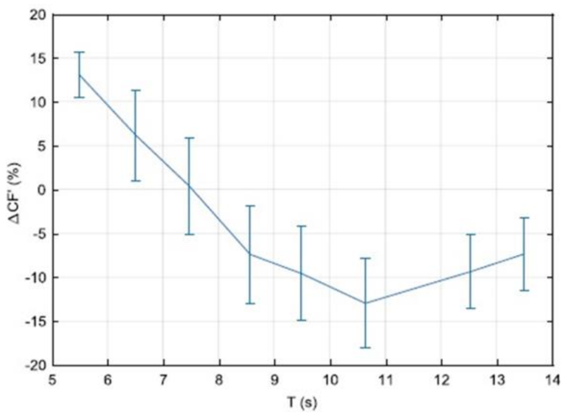


Figure 71. Percentage difference in Capture Factor of a modular flap relative to a rigid flap

It must be emphasised that these results are based on a very simplistic PTO control strategy, where the damping applied to each module is the same across the entire device. It is expected that the non-uniform motion response of the modules would lend itself to the implementation of a more sophisticated control strategy, where each individual module has a different level of damping applied. A preliminary investigation of this was presented in [I6] and shows the potential to improve power capture through non-uniform control of each module. Similarly, a preliminary quantitative analysis was also done on the experimental test results reported in [I10] from the OysterM project. Although performance gains were observed, only a marginal 2%-3% was reported. Nevertheless, there is scope for further exploration on this aspect of the device and quality control research may reveal noteworthy performance gains.

Another key result of the experimental tests reported by [I9] is that, the power smoothness of the modular WEC is significantly larger than a rigid flap. This is due to the natural out-of-phase motion of the modules. The smoothness was defined as the total mean power of the WEC (i.e. over all modules) divided by the standard deviation of the total instantaneous power. This can be regarded as a good metric for the quality of the power produced for conversion to electricity. Practically however, it does have the implicit assumption that conversion to electricity in the PTO system is on a per-WEC basis and not on an individual module basis.

3. **In head-on waves, the central modules capture the bulk of the power while the edge modules only have a marginal contribution to the power captured.**

From the early experimental observations of the behaviour of the modular WEC, it was clear that the central modules move much more than those at the edge. This is clearly illustrated in Figure 67 and Figure 70. This is the result of two effects. Firstly, for a wide structure in waves, the net fluid pressure is greatest at the centre of the flap (see Section [C3], Figure 40 in particular). Thus, for a modular construction, this means that the central modules experience a larger wave torque and so will be forced to move further. Conversely, the wave torque on the side modules is much less and so they will not move as far. Secondly, the edge modules will also be subjected to larger drag, turbulence and vortex effects as they move, thus retarding their motion even further. These mechanisms have the result that the edge modules do not contribute very much to the overall power capture of the WEC.

The experimental results of [I9] show that in a 6-module device, the central two modules produce 68% of the total power, the next two outer modules capture 25% and the edge modules only contribute 7% to the total power. A similar result was observed in the numerical simulation results of [I10]. Figure 72 shows an example of the individual power curves for each module in an 8-module device. (Note: M1 is the central module and the numbers increase to the edge module M7. The device is symmetric in the numerical model and so M2, M4, M6, M8 is the mirrored module locations which produce identical results). This shows a power split of 32%, 28%, 24%, 16% of the total WEC power from the central modules out to the edge modules respectively. Although this result shows the edge modules contribution more than that reported in the experimental results of [I9], it is thought that the viscous edge effects are not adequately captured in these numerical models. Nevertheless, it demonstrates the fact that the performance of the edge modules is poor. (It is also interesting to note the different optimal PTO damping points for each module, highlighting the capacity for performance optimisation through advanced control strategies).

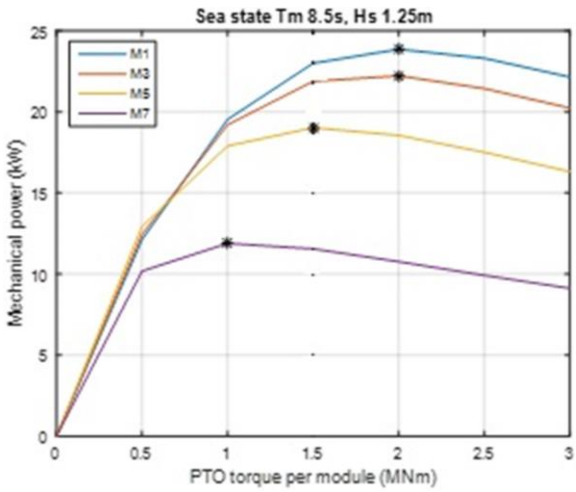


Figure 72. PTO Torque-Power curves of the individual modules in a symmetric 8-module flap.

The inherently poor performance of the edge modules, presents the opportunity to simply make those modules 'dummy structure' that do not contain valuable and expense PTO equipment. This idea was first postulated in [I3] through initial qualitative observations of the device operating in a wave tank. These edge modules would absorb the bulk of the negative drag and turbulence effects on the device and promote the performance of the central modules. A similar effect was observed and discussed in Section [C3], where vertical piles/columns place close to the edge of a flap enhanced the device performance via a decoupled the vortex and viscous edge effects.

4. **The parasitic foundation loads, both extreme and fatigue, on a modular WEC are dramatically reduced compared to an equivalent width rigid flap.**

A flap-type WEC is a force driven device. As such, power capture is intrinsically coupled with the magnitude of the forces induced on it. A flap's mode of operation (and thus power extraction) is in pitch and so it is only the Surge (horizontal force) and to a lesser extent the Heave (vertical force) that contribute toward power capture. Loading in the other degrees of freedom (Sway, Roll and Yaw) are classified as parasitic loads as they only provide 'pain with no gain'. Parasitic loads can have a significant effect on the structural design and cost of a WEC and so, a reduction in these will only serve as a benefit.

For the wide flap-type device, the Yaw load (twisting moment) induces racking forces across the structure and also has significant consequences for the foundation solution. A Yaw load is induced most severely in off-angle seas where, for a wide rigid flap, the wave crest impinges one edge of the flap well ahead of the other end, thus inducing a twisting moment. This effect is dramatically minimised in a modular flap as any asymmetric loading across the width of the WEC is taken up by the out-of-phase motion of each module. See Figure 73 for an illustration of the force diagrams on a rigid and modular flap in off-angle waves.

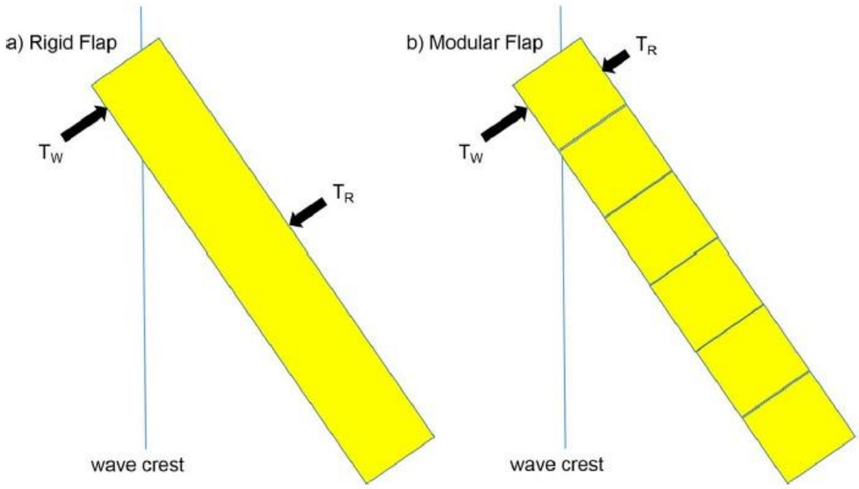


Figure 73. Force diagram of a rigid (left) and modular (right) flap in off-angle waves. T_W and T_R denote the wave excitation torque and body reaction torque respectively.

Extensive experimental wave tank tests were performed by [I7] on a 6-module flap (and rigid flap) in a range of irregular sea states and wave heading angles with spanned from 0^o to 45^o. The wave conditions tested were such that they were representative of two nearshore sites of interest to Aquamarine Power, namely EMEC in Orkney and a site off the Isle of Lewis. The wave climate at Lewis is more energetic and with a much larger directional spread.

Foundation loads in all six degrees of freedom (dof) were recorded. In each dof the Total Effective Load Range (TELR), which is a good metric for the fatigue damage caused to a structure and, the extreme/ultimate loads experienced in storm conditions were recorded. The results conclusively show a significant reduction in the Yaw load. A 70% and 50% reduction in fatigue Yaw was recorded at EMEC and Lewis respectively, with a 45% reduction in the extreme Yaw reported at both sites. Similarly, the Roll dof was also reduced by circa 25%. There was no appreciable change in the Surge, Heave or Pitch dof. Thus, a modular flap-type WEC has significant advantages over a rigid flap in terms of structural loading. This would likely carry over to a significant cost savings in the structural design and foundation solutions.

13.5 Outcome of the Research

From the various research strands, rich insights into the hydrodynamic characteristics (both power capture and loading), advantages and challenges of a modular flap-type WEC were gained.

Many sophisticated research tools were developed to investigated this multi-body device, which include: advanced analytical models; time domain numerical models and high-fidelity experimental wave tank models and testing techniques. These techniques and knowledge gain provide an excellent foundation for further research and development of this concept.

Triggered by the early academic research results, the OysterM project was initiated by Aquamarine Power in early 2015. A significant amount of engineering development was achieved on this concept, such as: structural design and fabrication techniques; PTO integration; foundation and anchoring designs; installation and maintenance strategies; and LCOE predictions. The overall concept was brought to a TRL of 3-4. The detail of the engineering activities and developments is beyond the scope of this report. Aquamarine Power ceased trading in November 2015 and as such, at this point all engineering development on this concept stopped.

13.6 References

[I1]. Wilkinson, L., (2017), "An Assessment of a Nearshore Modular Flap-Type Wave Energy Converter", *IDCORE EngD Thesis, University of Strathclyde.*

[I2]. Sammarco, P., *et al*, (2013), "A Review of all Research Work done on Modular Flap Structure", *External report commissioned by Aquamarine Power*.

[I3]. Henry, A., (2013), "130516 Initial Tests of the Finger Flap Concept - APL-RD.FDR.04-REP-0131 - A1", *Internal Report, APL*.

[I4]. Wilkinson, L., (2013), "130627 Very Wide Vertically-Modular Flap Report - APL-RD.FDR.03-EXR-0142 - A2", *Internal Report, APL*.

[I5]. Michele, S., *et al*, (2015), "Venice_Gate_as_a_WEC_Arbitrary_Thickness", *Applied Ocean Research, 52, pp 43-61*.

[I6]. Sakar, D., *et al*, (2016), "Sakar 2016 The Modular Concept of the OWSC", *Renewable Energy, 85, pp 484 – 497.*

[I7]. Wilkinson, L., *et al*, (2014), "J.11. Wilkinson - Wave Loads on The Foundation of a Bottom-Hinged Modular Flap Structure (ASRANe", *Intl. Conf. Offshore Renewable Energy (ASRANet), Glasgow, Scotland*

[I8]. Wilkinson, L., *et al,* (2015), "J.04. Wilkinson - Modelling the Performance of a Modular Flap-Type WEC (EWTEC, 2015)", *11th European Wave & Tidal Energy Conference (EWTEC), Nantes, France*.

[I9]. Wilkinson, L., *et al,* (2017), "Wilkinson_2017_The power-capture of a nearshore, modular, flap-type wave energy converter in regular waves", *Ocean Engineering, 137, pp 394-403*.

[I10]. van 't Hoff, J., & Doherty, K., (2015), "OYM-REP-0003 - OysterM parameter analysis - A3", *Internal Report, APL*.