CCell Mark 3 – Novel Curved WEC Optimisation

WES Novel Wave Energy Converter
Stage 1 Project
Project Report

Zyba Limited

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1 Project Report

1.1 Project Introduction

At its core, CCell wave energy converter is a light weight curved composite paddle that extracts energy from the surge motion of ocean waves. During the period from February 2016 to February 2017 the device has evolved to incorporate a seabed-hinged but otherwise rigid mooring that permits the paddle to rise and fall with the tides, and a curved horizontal plate added to resist heaving of the device.

The core project team consists of eight engineers and scientists across Zyba Ltd and The University of Bath, with Zyba managing the design, modelling and testing of the device and The University of Bath developing a small scale hydraulic damper for the laboratory trials. Specialist input and advice was also supplied by the University of Edinburgh (on modelling composites and reliability), Met Ocean Works (on site assessment), Frazer Nash (Advanced OpenFOAM training), Lloyds Register (on risks and fatigue), MPM Marine and Leask Marine (on operations), Independent Composites (on manufacturing composite models), the University of Strathclyde (on tank testing) and CFD-Direct (on OpenFOAM). The project has also been supported by four students, each on a 6 month industrial placement from the University of Bath and the École de Nantes in France.

The project has met all of its original goals including the delivery of 13 comprehensive technical reports. The development of the floating platform, around which the CCell paddle has been optimised, represents a major development for the concept, which has been hugely successful by most measures. The original CCell paddle, which extended to the sea bed, had limited applicability to shallow non-tidal sites, as tidal fluctuations would cause deviation from its peak performance. At low water the device would be susceptible to excessive loading in larger or extreme seas, whereas at high water the unit would potentially be fully submerged, leading to considerable overtopping and reduced power. The new design is flexible with regards to water depth variations, and though performance in longer period seas is reduced, it is overall more capable of sustaining its peak performance. Additionally it delivers substantial improvements to ease of installation, maintenance and survivability.

1.2 Description of Project Technology

The CCell WEC has evolved to contain three core elements: a paddle, heave-plate, and two rigid legs that form a capital A; with all three connecting together at the apex of the A (the A-frame), as illustrated in Figure 1. Power is generated from the relative motion between the paddle and heave-plate.

The distinctive curved paddle harnesses energy from the surge motion of the ocean waves, with the inner side of the curve facing the incident waves, and outer convex side facing shoreward. In use, the inner curvature channels the wave energy towards the strong spine of the paddle, along which power is extracted through the attached power take off (PTO) piston. The curvature of the paddle gives it significant vertical rigidity, which allows the walls of the paddle to be very thin and therefore lightweight. The paddle is also responsible for maintaining the device at an optimal vertical position in the water using buoyancy distributed within the paddle structure. Once localised reinforcement around attachment points for the bottom hinges and PTO are added, and the skin strengthened to enhance puncture resistance, then a full scale (10m x 5m) composite construction using glass-reinforced polymers (GRP) would weigh under 14 tonnes.

The height of the paddle above the free surface (free board) is an important aspect for survivability, as it allows excess energy from larger waves to overflow the top edge of the device. In addition the mean position of the paddle is pitched slightly forward to both prevent the occurrence of slamming on the inner face and promote overflow in larger waves. Although more power could be obtained with a cap on the device, slam loading on the cap became an obvious issue. The shoreward face of the paddle acts much like the bow of a boat and is superb at cutting through the water while minimising the radiated energy loss associated with this movement. This profile all but eliminates the possibilities of slamming loads on the shoreward face. The paddle is the only element of the CCell WEC that traverses the splash zone, with the GRP construction providing excellent resistance against corrosion.

The paddle attaches to a T-shape section through a set of parallel hinges and the PTO piston. The T-section is also hinged at either end onto the underlying base (A-Frame), and this allows both the T-section and paddle to roll. This freedom in roll helps the paddle to absorb side loads without transmitting any high transverse torques into the base structure. This in turn simplifies the paddle hinge assembly and significantly reduces side loads on the piston rod due to distortion of the structure. More importantly, as the device is raised in the water (using buoyancy tanks in the heave-plate), the roll causes the paddle to “flop” to one side and support itself. This halves the load that must be lifted to expose the PTO assembly and bearings for maintenance, while also making these components accessible to a vertical lift from a vessel crane.

The Heave-plate is also manufactured from composite GRP and is a broadly horizontal plate with a gentle downward curve. It is positioned mid-way down the water column, usually between a half and two-thirds of the water depth. This plate resists pitch motion of the A-frame, by limiting heave at the top of the A. The heave-plate also sits shoreward of the paddle, such that a upwards hydrodynamic loads on the heave plate are approximately in phase with the horizontal forces on the paddle, and vice versa. Beneath the heave plate are two small tanks that are usually flooded, but during maintenance and inspection can be filled with air to raise the entire heave-plate to the surface. In this mode, the heave plate forms a substantial platform against which a small boat can be moored and maintenance of the entire PTO assembly safely carried out.

The legs of the A-Frame are rigid and are manufactured from either steel or composite tube. The bottom of each leg connects to the foundations, through a set of bearings that allow the A-frame to pitch. This motion allows the entire device to adapt to tidal variations and permits the raising of the system for maintenance. The legs also carry any cables or pipes from the sea-floor to the top of the A-Frame.

The final element of the system is the PTO, which is envisaged to be hydraulic. Crucially this is expected to provide dynamic control of the paddle motions to enhance power capture within irregular seas. The low mass and inertia of the paddle simplifies this task allowing the system to respond very quickly to changing circumstances and PTO control. For example, with an extreme wave the PTO can quickly relax to reduce energy capture and promote over-topping. Due to the asymmetry between crest and trough loads, and the overall geometry of the system, it is also selfregulating: automatically sitting lower in the water in heavier seas. This change in free-board dramatically improves survivability by increasing energy loss through overtopping.

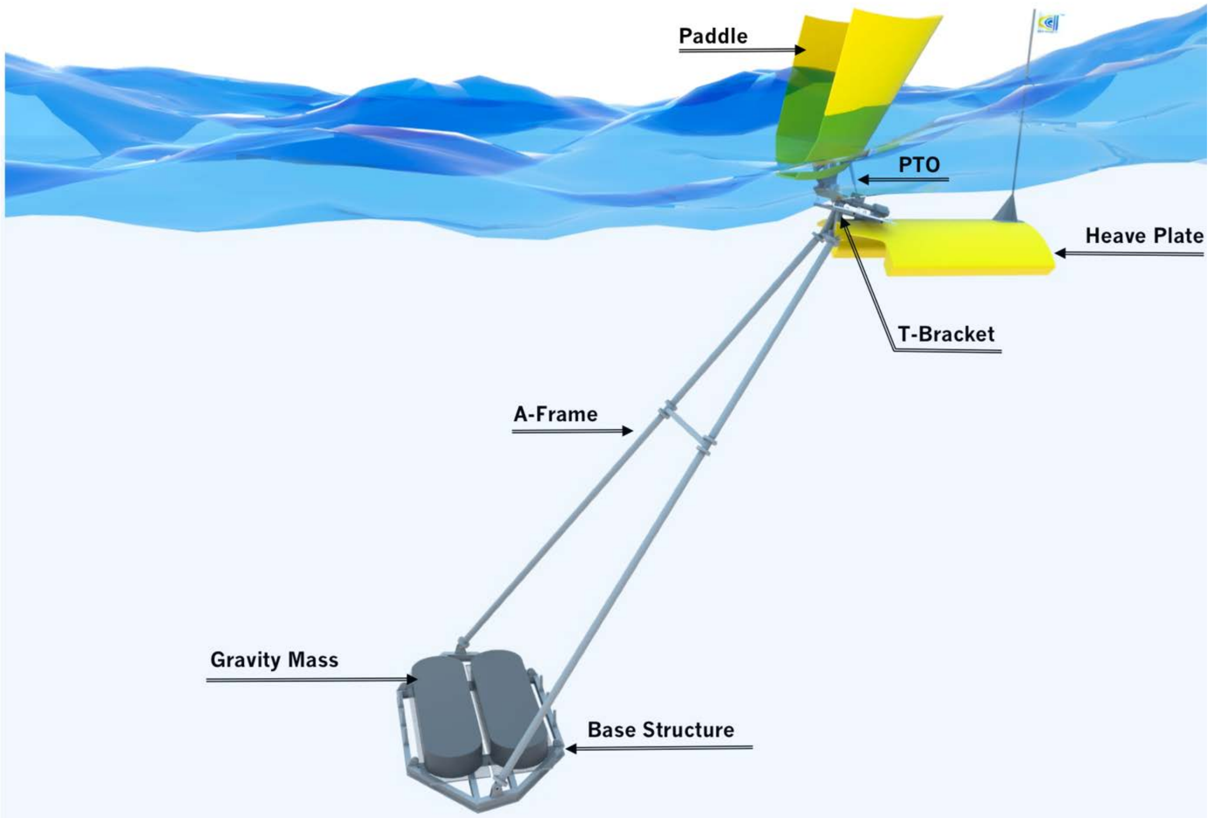

Figure - Illustration of the floating CCell concept.

1.3 *Scope of Work*

The team pursued an iterative approach to the project across three overlapping phases:

- Concept development and exploratory testing
- Design optimisation and performance testing
- Full scale concept design

The first phase involved five parallel work streams:

- Hind-cast modelling of the wave conditions near Eigg, the chosen reference site, to obtain 32 years of hourly wave data (Hs, Tp and Direction) and extreme wave heights at three water depths off the south-west coast of Eigg. The data, alongside the sea-states requested by WES guided the optimisation of the device. Reported in D1.
- The development of analytical model to explore the coupled motions of the paddle and heave-plate, and the impact of varying the geometry and relative position of either system. Reported in D2.
- Design and manufacture of three paddle designs, including a flat paddle, a paddle curved around a vertical axis, and a paddle with curvature around both a vertical and horizontal axis forming caps on the top and bottom of the device. The purpose of testing all three shapes was to provide a link back to previous testing of similar paddles that extended through the water column from the sea bed, and provide three distinctly different geometries to support calibration and validation of both analytic and CFD models. Reported in D5.

- Validation of CFD modelling against experimental data for three paddle designs (noted above). Reported in D4
- Design of a laboratory scale hydraulic damper to absorb power during the laboratory trials. Reported in D3.

Though technically outside the scope of this project, a further stream of work (funded by Innovate UK) simultaneously looked at a range of base designs to enable the paddle to rise and fall with the tide. Crucial to the success of both projects was early confirmation that the A-Frame concept would work as anticipated, which was confirmed during initial trials in May. The first detailed laboratory trials were undertaken in June, with all three paddle designs tested alongside a variety of heave-plates on the newly design A-frame.

The second phase of the project undertook a much more rigorous optimisation of one paddle using CFD. This work reported in D8, explored four aspects of the paddle design to enhance performance (power per cost), including the:

- Depth of the paddle hinge
- Relative dimensions of the curved paddle in each direction (x,y,z)
- Size of a generally flat horizontal shelf at the bottom of the paddle
- Mean pitch of the paddle.

The optimised paddle shape, alongside an improved A-frame, PTO Damper, and heave-plate were then manufactured and tested in October. The focus on these trials was to prepare for the final performance testing in November, by tuning the configuration. Most notably this explored: the distribution of buoyancy between the heave-plate onto the paddle; the optimal mean orientation of the paddle; its performance in large nonlinear waves; and ideal damping values to enhance energy extraction in regular sea-states. The roll mechanism was also successfully tested for the first time in directional seas. Final performance testing took place in November, with a newly manufactured paddle with the optimised buoyancy attached. Reported in D11.

The final phase of the project concerned the full scale design of the device, including the reliability for key component, an assessment of deployment and maintenance operations, and technology risk. Reported in D13.

Figure 2 illustrates the key reports delivered to Wave Energy Scotland and the interconnectivity between activities.

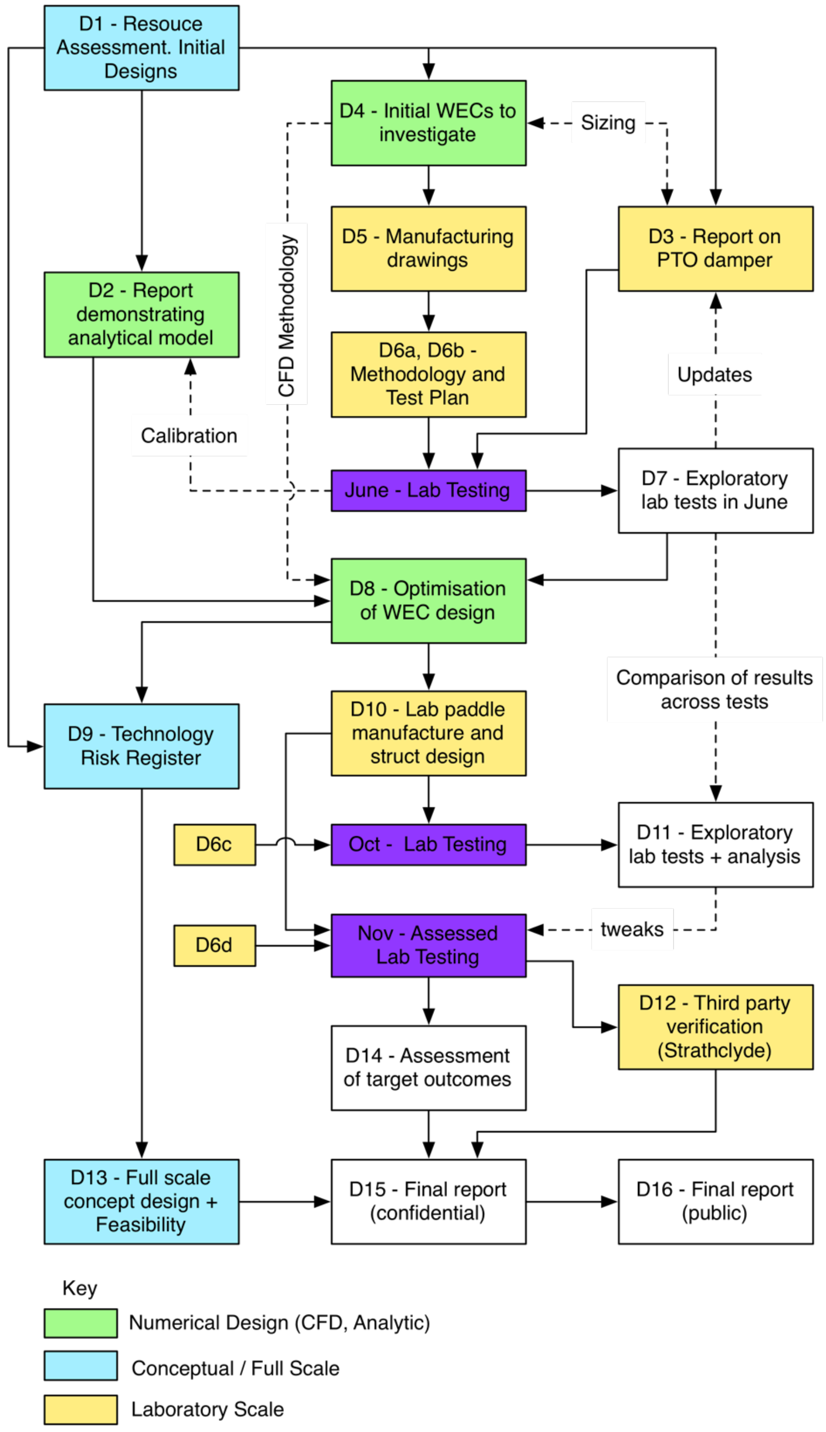

Figure 1 - Scope of Work - Public

1.4 Project Achievements

The first stage of the project went very well with early completion of the resource assessment (D1), analytical modelling (D2) and the PTO damper design (D3). However, the simulation of different paddle designs using CFD was hindered by a range of issues that effected the dynamic simulations for target design sea states. Due to the long run times for CFD (often days) these issues took time to trouble-shoot and resolve, which delayed later phases of the project. Once resolved the paddle shape was further refined in a parametric study.

The introduction of the A-frame, and confirmation of this design in June, represented a substantial step-change for the CCell concept, addressing many challenges relating to installation, maintenance and survivability of the system. In the design of the A-frame, the team was keen to identify a solution that avoided the need for complicated catenary moorings, or the use of divers during either installation or maintenance, while also allowing maintenance activities (even for a large device) to be undertaken from small vessels. All these goals have, at least in theory, been achieved and the marine operations strategy was reviewed by Leask Marine.

Early attempts to implement the roll feature of the T-section were unsuccessful, largely due to a simple miss-calculation of buoyancy distributed around the system, which made the system unstable. During early laboratory trials the roll mechanism was locked, so this didn’t impact other research. Once the buoyancy was adjusted, the roll system worked perfectly – indeed during performance testing, it was not visibly obvious that this feature was enabled – yet it dramatically reduced torsional loading in the A-Frame, especially evident in directional seas.

The hydraulic PTO damper, with dynamic control, evolved quickly through each of the laboratory trials. The early version of the system was bulky, with the control valves positioned on the gantry and connected to the device through long hydraulic hoses. This was improved for the final testing in October and November where the control valves were discretely attached to the upper-edge of the A-Frame, with only a single control cable connecting to the gantry. The dynamic control incorporated into the PTO system worked well after initial teething problems: when in use it was able to rapidly maintain the paddle around a mean position and continually refine damping in each direction to maximise power output. The system was used in this way to find the optimal mean valve settings prior to performance testing.

The performance from the final laboratory studies was broadly in line with expectations, with up to 65% of energy extracted from the short period (T=7.7) WES irregular sea-states, versus the 60% we estimated pre-project. In longer periods, approximately 28% of the energy is captured, dropping to 12% in the highest period wave (Tp=14.7). The trade-off in having a shorter paddle operating at the water surface, is that it is unable to extract the energy that passes beneath it, especially that associated with longer period waves – such as swell. To tune the device performance for these low frequencies requires extending the height of the paddle and lower the submerged hinge position. However, this is not necessarily the most cost efficient solution.

Given the enormity of the challenge in costing the manufacture of a full-scale device, Zyba selected to undertake first a conceptual design at 1/3 scale, for which quotes for manufacture and components costs are more readily available. These values have then been scaled to full-scale. Assessing the reliability of components on the WEC has been difficult, largely due to a lack of data from equivalent systems in the marine environment. To address this uncertainty a temporal stochastic model has been developed using the Weibull distribution to provide variance around the mean times to failure for each of the main components.

Overall the project has achieve all of the initial objectives, with a focus on optimising the performance of the lightweight CCell WEC. In addition, a viable strategy for deployment and maintenance has been developed.

1.5 Summary of Performance against Target Outcome Metrics

Affordability

Capital costs for a first-of-kind full scale unit have been extrapolated from a 1:3 scale concept design, which was based on manufacturer quotes and estimations. Current estimations for the CAPEX are £4,670/kW, approximately 15% higher than the initial stage 1 targets.

From an assessment of reliability, a stochastic simulation of operations and maintenance (O&M) activities, calculates an annual OPEX of £55.3/kWpeak. This leads to an LCOE between £558/MW and £247/MW based purely on scaling the performance from laboratories trials to the sea conditions at Eigg and Wave Hub, respectively. It the device at Eigg is stretch in height, with the paddle sitting lower in the water, then it is believed that this would increase performance at lower frequencies at the expense of less power in higher frequencies, leading to a LCOE closer to £274/MW. These value contrast well with the initial project target of £400/MW.

Performance

The performance of the CCell was assessed across four rounds of laboratory testing, with incremental improvements made to the device after each round. The power captured by the device in different sea states was used to determine an efficiency matrix for a wide range of conditions, exceeding 80% efficiency in high frequency waves (as illustrated in Figure 3). In irregular seas, the CCell WEC capture between 27% and 52% of available energy, compared to a target outcome of 60% set at the start of this project. These numbers are based on fixed damping values, which represent sub-optimal tuning of the PTO. Optimised control strategies and geometric tuning to prevalent site conditions are expected to improve these results in line with the original target outcome.

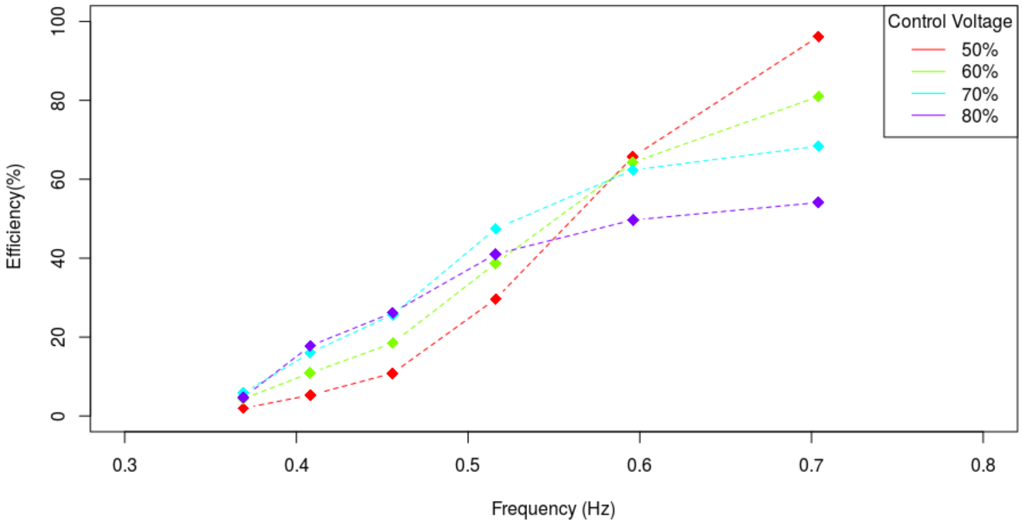

Figure 2: Efficiency of CCell at different levels of fixed damping (100% represents a freely moving system and 0% represents a fully damped motion) - Public

Availability

The stochastic LCOE model developed for this project, estimates there will be 1.7 interventions per year, in addition to annual scheduled inspections, leading to an overall availability across the year of 96.2%. This equates to 9% loss of annual energy generation, due to a winter bias for failures that take longer to address.

CCell has been designed to simplify maintenance operations, with the ballasting tanks pumped with air to raise the device to the surface, avoiding expensive lift operations offshore. The T-section allows the paddle to roll to its side in this arrangement allowing 'dry' access to the majority of the critical areas. Inspections and minor repairs can therefore be carried out by a small vessel without lifting equipment. While larger ships may be required for more major repairs, the reduction in cost for smaller repairs and inspections is significant.

Survivability

The survivability is an intrinsic element of the design, including the following features:

- The paddle is designed to encourage larger waves to over-flow the device, with the paddle having shore-ward pitch to help larger waves pass over the device.
- Slamming is limited by avoiding large vertical planar surfaces. The shoreward face of the device is curved much like the bow of a boat, allow it to cut through waves. While water entering the seaward face is gradually focussed inwards and upwards leading, with a gradual transfer of power from the wave to the paddle. This means the paddle is always moving with the wave before the main crest meets central inner face of the paddle.

- For peak performance the paddle should be fairly relaxed, which means that when a sudden extreme force is detected, the control system only has to release the resistance a little to allow the paddle to move freely – allowing it to disperse energy from the shoreward side.
- The roll of the T-Section, stops the absorption of side loads, that would otherwise transmit significant forces into the base of the structure; and potentially also cause slamming on the side from crossing seas.
- During heavier seas the asymmetry between crests and trough forces increases, which cause the entire WEC to be pitched shoreward. Due to the positioning of the A-frame hinges, this forces the paddle down, reducing its free-board and thereby increasing over-flow and the maximum power the paddle can extract.

Overall the structural elements have been designed around a 1:100 year extreme wave with the PTO piston assumed to be locked, which results in the largest stresses across the system. In practice it is a very unlikely set of conditions.

1.6 Communications and Publicity Activity

[Describe any public promotion of this technology, such as academic papers and posters, press releases, news coverage etc.]

News Coverage:

- W.Bateman, Interview with Shipping 2030. “The Wave of the Future? Innovate Will Bateman Explains Wave Energy”. 7th December 2016. https://shipping-2030.com/2016/12/07/the-wave-of-the-future-innovator-will-bateman-explains-wave-energy/

Conferences and Papers:

- Dhruv Raj Chandel, N. Sell, A. Hillis and A. Plummer. Simulation and modelling of an oscillating wave surge converter using Boundary-Element methods, 3rd PRIMaRE Conference 5-6 July 2016, Bath.
- James Bridgwater, A. Hillis, A. Plummer. Coupled Simulation of Hydrodynamics and Power Take-off Dynamics for Ocean Wave Energy Converters , 3rd PRIMaRE Conference 5-6 July 2016, Bath
- Dhruv R.S. Chandel, Nathan P. Sell, Andrew R. Plummer, Andrew J. Hillis. Discrete Control of an Oscillating Wave Surge Converter, UKACC Control 2016 31 August - 2 September 2016, Belfast.
- W.Bateman, Extreme Wave loads on Wave Energy Devices, All Energy, 5th May, SECC Glasgow.
- W.Bateman. Progressing to Commercialisation, MARINE 2016, Inverness, UK.
- W.Bateman. WES Conference and Poster. 2nd December 2016

Submitted Papers for 2017:

- EWTEC 2017: Performance analysis of the CCell wave energy device
- EWTEC 2017: Adaptive Control of the CCell WEC
- EWTEC 2017: Composite Design of a Curved OSWEC
- EWTEC 2017: Modelling of Array Interactions for a Curved OWSC using OpenFOAM

1.7 Recommendations for Further Work

The key areas for further work include:

- The existing CFD code is limited to modelling systems with one degree of freedom. A recent update to OpenFOAM (sponsored by Carnegie) now allows multi-body system to be simulated. To enable the full simulation of the CFD WEC we need to adopt this new code and work with CFD-Direct to enhance this capability.
- OpenFOAM doesn't currently support an input for full-nonlinear waves. Zyba is working with CFD-Direct to incorporate boundary conditions necessary to accurately simulate extreme waves.
- Existing CFD work has assumed laminar flow. A short study was undertaken with various turbulent models, which led to radically different results depending on the initial parameters chosen. Research on the appropriate selection of both the turbulence model and parameters is needed, particularly when modelling the flow around the tips of the paddle.
- Existing CFD assumes a constant damper; however, we have now characterised the performance of a hydraulic damper in software. This needs to be integrated and tested within CFD.
- Modularity of a full-scale system will simplify manufacturing, transportation, potentially also maintenance. However, the interconnection between composite elements in a marine environment raises a series of challenges that need to be further researched.
- Fatigue in composite elements has not yet been modelled. The long term performance of composite in the marine environment is complex and requires specialist input and careful design.
- The shape of the heave plate needs further optimisation to improve both its rigidity and hydrodynamic performance. In particular, further modelling is required to investigate the behaviour of the A-frame and heave plate in transverse and crossing seas.
- The tubular members that make up the A-Frame are currently assumed to be steel. The use of composites could provide a similar strength but with increased resistance to corrosion. The cross-section of the tubes could also be optimised to improve resistance to buckling while enhancing strength at joins. Also the resistance of composites to abrasion from floating debris (sands, rocks etc) needs to be understood.