The Mocean WEC

WES Novel Wave Energy Converter
Stage 1 Project
Public Report

Mocean Energy

This project has been supported by Wave Energy Scotland

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1 Project Report

1.1 Project Introduction

The Mocean wave energy converter (WEC) takes its inspiration from the classical symmetrical hinged raft WEC. The classical raft comprises two hulls joined with a hinge, floating in the sea surface with the hinge parallel to the wave crests; the hulls are symmetric about the hinge axis. The Mocean WEC improves on this by making the hulls asymmetric, with very different size and shape. We have demonstrated with physical models that this can double the wave power absorption – and numerical models suggest the increase can be three times greater or more.

Wave Energy Scotland, within its Novel WEC programme, have supported a project for a preliminary investigation of the Mocean WEC. The project team comprises: Mocean Energy (the lead contractor); the University of Edinburgh, whose Institute of Energy Systems (IES) provided expertise in numerical hydrodynamic modelling and technology assessment and costing; Pelagic Innovation and AJS Engineering, who carried out the concept engineering of a full-scale machine; and Sequentec, who developed the control hardware for the physical scale models.

The project began with the aim of creating a WEC that was practical, survivable, affordable and had good power conversion performance. The necessary balance between these goals was achieved and the result is a machine that is robust and effective, while developing innovative numerical models that provide excellent insight into the hydrodynamic processes and point the way to yet further gains.

1.2 Description of Project Technology

The Mocean WEC is a hinged raft, two floating hulls connected by a hinge parallel to the wave crests. The wave excitation forces and the bodies' dynamic responses cause a relative motion between the bodies about the hinge; power is extracted via a power take off (PTO) system built into the hinge.

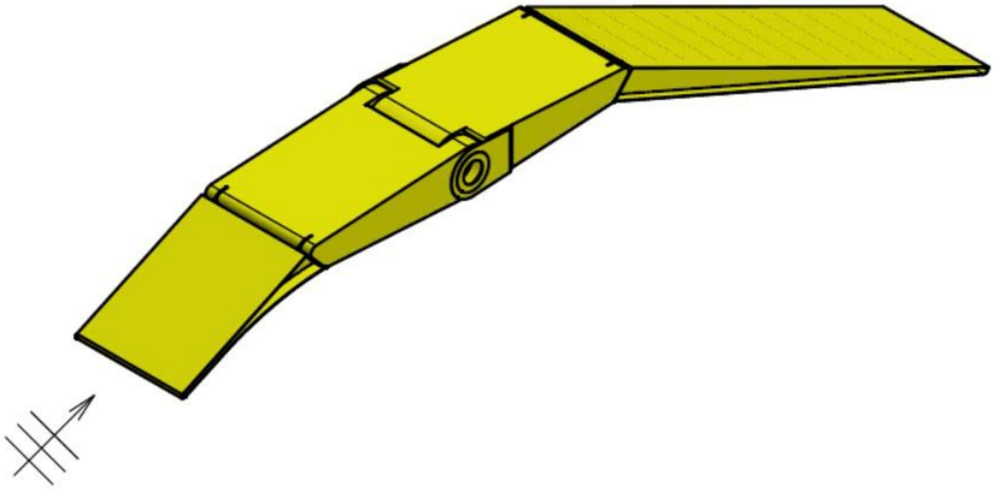

Figure 1: The Mocean WEC with nose and tail flaps - waves shown approaching from left

The innovation is in the shape of the hulls, which are quite different from the standard box, tube, or cylindrical hulls seen on other hinged-raft WECs. They are characterised by 1) the fore and aft hulls are different in size and shape from one another; 2) they have a sloped submerged nose, and/or 3) sloped submerged tail; 4) either or both of the nose and tail may be composed of a thin plate. The depth to which the submerged nose and tail reach below the still water surface is significant, and they act as upside-down flaps, so that the device is like a cross between a hinged-raft WEC and a floating-flap WEC.

The design focus of the Mocean WEC has been on utilising hydrodynamics and body dynamics to maximise power absorption at the primary interface, that is, where kinetic and potential energy in the fluid is converted to kinetic energy in a moving body. By their extension into the fluid, the submerged nose and tail greatly increase the hinge excitation moment caused by the waves. The submerged nose and tail act like flaps and experience both a surge and a heave force due to the wave; whereas flat-bottom, hinged-rafts only experience a heave force.

By virtue of being different sizes and asymmetric in shape, the component bodies of the Mocean WEC induce a coupling between modes of motion due to inertial, hydrostatic, added mass, and damping forces. Consequently, motions in heave and pitch cause a flex about the hinge. Furthermore, there is a strong resonant response that can be tuned to the wave frequency of interest. This tuning of the response is complex and, so far, has been accomplished implicitly using the numerical geometry optimisation suite.

The sloped faces of the WEC have a nonlinear response in waves, which is a natural load limiter. As waves get larger, the body motions increase proportionally less, and the waves eventually overtop the device. The means the PTO can be sized to be smaller and will operate at a higher proportion of its rated capacity more of the time, i.e. it has a higher capacity factor and so is more economical. Moreover, thanks to its deeply submerged nose, the device dives through the steepest waves, neither emerging from the water surface nor re-entering it, thus avoiding slamming loads.

1.3 Scope of Work

The four main strands to the project were:

1. Develop a numerical model that accurately models the geometry, kinematics and dynamics, and the hydrodynamics of the WEC. Use this numerical model within an optimisation to evolve new geometries – i.e. hull shapes.
2. Build and test physical scale models both to validate the numerical model and to follow intuitive insights into physics in order further to improve the WEC.
3. Assess known WEC technologies and apply the most promising of them to a concept of how a full-scale version of the Mocean WEC could be engineered.
4. Analyse the concept engineering product in terms of its annual electricity production and its capital and running costs in order to derive a cost of energy figure.

The reasoning behind the selection of these four topics was as follows.

Numerical modelling depends upon a formal mathematical investigation of the physics and its implementation in code; this in turn promotes further physical understanding. A test of the model validity is how well it predicts the performance of the WEC – and of hitherto unexpected phenomena. Linear-wave numerical solutions (as opposed to computational fluid dynamics simulations) of the hydrodynamics were developed, in both the frequency and time domains. The speed of this linear-wave code allowed it to be used to scan large numbers of different body geometries and even to perform optimisations of those geometries. This is far faster and more efficient than building scale models and physically testing them.

Nonetheless, physical model tests are invaluable for several reasons. Firstly, notwithstanding that the tests are performed at reduced scale, the model is a still physical object immersed in water and exposed to real waves; this gives considerable reassurance that the observed behaviour of a full-scale machine is likely to be similar. Secondly, it can validate the predictions of the numerical model. Thirdly, the observations of the behaviour of the model and the surrounding water can help explain discrepancies between the numerical and physical models. This is particularly true for non-linear effects such as those related to the varying submergence of the model, or for entropic effects such as turbulence and wave breaking. Finally, close examination of model behaviour can assist in design changes to mitigate undesirable effects in the functioning or operation of a full-scale WEC.

Full-scale concept engineering provides a reality check on the research. Is the concept practical at large scale? What challenges are there to the construction and operation of such a machine? How much energy will it produce and how much will it cost to build, deploy and operate? The concept engineering task requires considerable expertise and research to pull together the physical and commercial data on all the subsystems and to ensure that their synthesis is achievable, workable and affordable. The three largest cost categories (accounting for around 95% of the total cost) are the structure, the power take-off (PTO) and the installation of the machine at site. The particular challenge to address is that the prime mover of the WEC, which interfaces with the water, has to accommodate very high reciprocating loads at very low velocities. Fatigue loading dominates and high-ratio gearing is required. This places huge demands upon the structure and PTO, which have to be highly efficient in their use of materials and handling of force and power.

The costing study provides the accountancy bottom line – how much energy can be produced at what cost? It requires several inputs: meteorological data on the wave climate for prospective sites; the WEC's power matrix (its effectiveness at turning the energy in the waves into electricity, at given values of wave period and height); the cost of the structure and PTO components specified in the concept engineering; and the cost of the operations at sea necessary to install, operate and maintain the WEC. Because the engineering is challenging and the wave energy industrial sector is but nascent, the component are expensive or perhaps even available only as a bespoke order; parametric costing, based e.g. on prices per mass of similar fabricated components in related industries, may have to be used. And, to determine the economics in the long term, learning rates will have to be applied, again by analogy with related industries.

We correctly anticipated that synthesis and cross-fertilisation of these four project areas would provide healthy evolutionary pressure on our development of the Mocean WEC.

1.4 *Project Achievements*

Numerical Modelling and Optimisation

The numerical model successfully formulated the kinematic constraints on the component bodies comprising the asymmetric raft, the resulting dynamics and the hydrodynamic excitation forces. This allowed predictions of the modal response and the power production early in the project. Coupled with the interfacing of the description of the hull shapes in the proprietary CAD package Rhino and the derivation of hydrodynamic coefficients of these shapes in the proprietary hydrodynamics software WAMIT, it was possible to examine the performance of a large number of WECS of widely varying shapes. This in turn allowed the optimisation of WEC shape for power production against simple cost indicators such as overall mass of the machine. Some of the resulting WEC contenders were high performers with unexpected shapes, subsequently explored in physical scale models.

Physical Scale Model Testing

We constructed a range of WEC hull shapes, previously identified as promising by the numerical work, connected them to a hinge power take-off that could apply damping restraint, and tested the resultant model WECs in wave tanks. We tested at two scales, 1/50th and 1/20th. The results broadly confirmed the numerical results with regard to the frequency response, i.e. the location of the resonant response was correctly modelled. However, absorbed power was less than that predicted by the numerical model, apparently owing to non-linearity and other effects. When these were reduced by the addition of side-plates that suppressed the 3D flow, the power absorption increased. More generally, comparison of the experimental results with the numerical predictions convinced us that the performance could be improved by further physical changes to reduce non-linear loading.

In respects other than power production, the response of the physical models reassured us that the behaviour of the design was generally benign. It appeared to have unconditional static and dynamic stability, with no hint of any tendency to capsize. In large waves, it had a natural tendency to shed load by allowing the passage of waves over the top of the hulls (overtopping). Even in the largest waves the hinge motion was much less than the hinge limits, nor did the nose of the WEC ever leave the water, so there were no air gaps and no risk of slamming. The self-referenced nature of the design – i.e. the two hulls react mainly against each other rather than the mooring means that mooring loads are low and second-order, i.e. the mooring displacements are low-frequency, well below the wave frequency.

Concept Engineering

This was an opportunity to survey a range of relevant technologies, to assess their relative merits and to develop a deeper understanding of the design constraints.

For the study, we selected steel as the full-scale hull material because of the extensive knowledge of its properties. Moreover, for a prototype, it has the benefit that design modifications may be incorporated even at a late stage of construction. However, other materials, such as concrete, may have cost, performance or constructional advantages. Having selected steel and knowing the shape of the hulls and (from the numerical model) the distribution of loads over their surfaces, a finite element analysis was carried out to determine the optimum layout of the superficial steel sheet and associated welded stiffeners, to explore the distribution of stresses, to optimise then finalise the structural design.

We were keen to have a power train that was mechanical to electrical, with no intermediate pneumatic or hydraulic elements. This was partly to avoid losses, partly to reduce the component count, so potentially improving reliability. Furthermore, we foresee electrical drive being able to provide improving controllability as the capacity of power electronics continues to increase. Permanent magnet generators (PMG) were selected as the most attractive technology. However, they are not commercial off-the-shelf products, so their cost must be estimated parametrically.

The main hinge was designed to optimise the support for the shafts against the known large loads and optimise the load path into the hulls. However, the cost of the individual bearings is significant and they, as well as the hulls, must be protected against water ingress by effective seals.

Costing Study

This gathered wave climate data from 5 potential wave farm sites and calculated annual energy production by combining each climate with the power matrix of the base design, conservatively specified from the experimental scale model results rather than the numerical model predictions. The energy production was greatest in the most energetic climates, as would be expected, but the machine could be reconfigured for the less energetic sites by reducing its size.

The parametric costing of the PMG indicated a cost benefit: reducing the size of the machine reduced its cost pro rata but initially gave rise to merely marginal decreases in annual energy; it was therefore possible to determine a cost/benefit optimum.

The steel structure was also costed by mass but it was not possible to determine a similar optimum because that would have required iterating the structural finite element analysis, which was a time-intensive, one-off calculation.

Installation is well known to be a substantial cost centre and, following practice established in the literature, was estimated here as a percentage of the capital cost of the WEC. For the base design, the relative costs of structure, PTO and installation were approximately 40%, 30% and 25% respectively.

The study clearly pointed to the possibility of cost reductions by optimising the structure, much as the PTO had been optimised, and examining the use of alternative materials. For example, concrete is an order of magnitude less expensive than steel, although it would require a greater mass of material and greater investment in the associated production equipment.

1.5 Summary of Performance against Target Outcome Metrics

Performance

The Mocean WEC can produce significant power for a small size. This is due to the unique geometric shape which induces a high excitation force per unit mass, and cross-coupling between modes of motion.

Survivability

The Mocean WEC has high inherent survivability. The PTO has infinite rotation – it has no end-stops. The hinge rotation is ultimately limited by the geometrical interference of the two hulls – but the allowable angle range is many times greater than the angles experienced by the model in the steepest seas, even in the worst case of control failure, i.e. zero damping.

Overtopping reduces the hydrodynamic loads on the structure. This load-shedding feature also has the benefit that the machine does not have to have an uneconomically high generator peak rating and so will deliver a higher capacity factor.

The nose has unconditional positive draft, i.e. it always remains submerged. No air gaps appear beneath the hulls; therefore, there is minimal risk of slamming and the consequent damage.

Reliability

The Mocean WEC has just two bodies and a single hinge, thus a low component count, contributing to improved reliability. Some redundancy is provided by using two generators and their associated power trains. The WEC is self-referenced, with a highly compliant mooring that has a resonance period much longer than typical wave periods and so generally decoupled from wave-frequency loading

The permanent magnet generator PTO was selected to provide a high reliability system. It is conceptually simpler than alternatives such as hydraulic systems and eliminates an energy conversion step (mechanical power is converted directly to electrical power, without an intermediate step).

The bearing systems are relatively simple, operating in a single degree of freedom (pitch). They are intended to be sealed from the marine environment, and with an appropriate lubrication system should display a reliability and life that meets or exceeds the current ‘best in class’.

Affordability

The LCOE for the machine has been calculated as around 300£/MWh using the costing model released by WES. We believe that the LCOE can be halved in the next design iteration. There are several possible contributions to this, discussed in the Recommendations for Further Work.

1.6 Communications and Publicity Activity

Poster at National Hydropower Association Water Power Week, Washington DC, April 2016.

Poster at WES Novel WEC conference, Edinburgh, 02 December 2016

1.7 Recommendations for Further Work

Performance

The linear numerical model predicts roughly twice as much energy yield as do the physical model tests. The difference is attributable to nonlinear effects, which include viscous stresses and shedding, turbulence and overtopping on the sloped nose and tail, and hull geometric effects. We believe we could greatly improve the performance of the Mocean WEC through a better understanding and a subsequent mitigation of these effects.

The first step in this would be an experimental investigation at small scale with controlled tests. For example, they could measure the excitation force on a range of Mocean WEC hull shapes. The experiments would improve our understanding of the effects and inform numerical model validation. Nonlinear effects could be incorporated into the linear model by, for example, linearising Morison forces.

Another avenue to performance improvement is that of control. It has long been known that simple damping control for WECs – as used in our numerical and physical models – are much surpassed in performance by complex control. We believe this is a very rich area of research with potential for very high performance gains.

Costs

The capital cost is dominated by 1) the structure, 2) the PTO, and 3) installation.

We have the most direct control over the structural cost, which is also the largest cost centre. We would like to undertake a general study of material substitution and structural reassessment to identify and quantify cost savings. For example, concrete has an order of magnitude lower cost than steel.

The PTO and its cost is central to the overall system design of the Mocean WEC. We could work with PTO developers to gather more information as to how the costs of rotary PTOs relate to the torque. This information and other performance and costing inputs derived from concept engineering would then be incorporated as cost functions in an updated techno-economic optimisation, expected to lead in turn to WEC designs with lower cost.

The Mocean WEC is self-referenced: the mooring is decoupled from wave-frequency loads. This much increases the freedom to explore novel mooring topologies. As mooring and installation are a significant cost centre for WECs, we believe there are large potential savings. Future work would continue to measure mooring loads in extreme conditions to estimate their effect on cost and would simulate and optimise installation and operation and maintenance scenarios.

Survivability

Structural loading will benefit from further investigation and optimisation. At present, the structure is designed to sustain the lifetime fatigue as this is the most likely loading limitation. It will be necessary to confirm the ultimate load cases in extreme waves. It will also be of interest to refine the overtopping characteristic of the machine to control peak and fatigue loads while increasing power absorption. This is inherently a non-linear challenge, likely best addressed by physical model tests.