WaveTrain

WES Novel Wave Energy Converter
Stage 1 Project
Public Report

Joules Energy Efficiency Services Ltd.

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

The WaveTrain WEC is a linear array of several floating wave activated bodies utilising a collection of parallel inclined tubes, open at the bottom but closed with a canopy at the surface and utilising a simple pneumatic turbine power take-off system. The individual power modules are interlinked by a tubular 'A' frame coupling member with flexible joints top and bottom. The power modules are spaced approximately half a typical wavelength apart so that balancing self- reaction support is achieved. The project aims to validate through the use of advanced numerical models and scale model wave tank testing the expected high device efficiency to produce a competitive cost of delivered electricity.

The original concept of an inclined plane power (IPP) buoy with pneumatic power-take-off (PTO) system was proposed by Dr Nicholas Wells during 1999 operating under the development organisation, Joules Energy Efficiency Services Ltd (JEES). Scale model tests of the IPP buoy were undertaken between 2000 and 2001, with narrow tank tests taking place at Queen's University Belfast (QUB) funded under an Invest NI SMART Award to JEES and with wide tank tests taking place in Inverness.

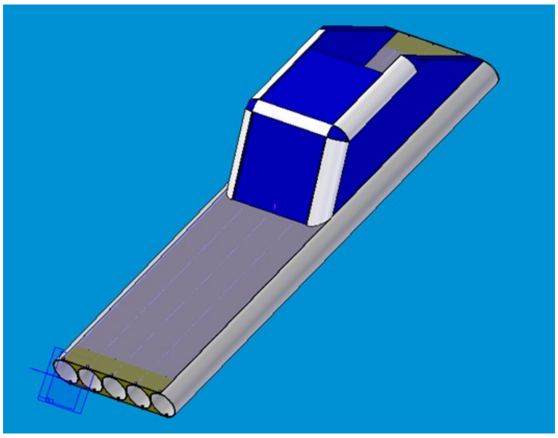

Figure 1.1: Original concept of an inclined plane power buoy
(CAD Image copyright Joules)

These tests were followed by a hydrodynamic assessment of the IPP buoy using the WAMIT computer programme in 2002 before development was put on hold until April 2009 whereby the 'WaveTrain' device concept was conceived by JEES. The concept was reviewed positively by Black & Veatch under the Carbon Trust MEA Stand A programme in 2010 in a Mini-Initial Device Assessment. Tank tests were subsequently undertaken at HMRC under the MARINET programme in 2012 on a 1:50 scale model of the WaveTrain array and the extensive results were analysed by Stewart Irwin from QUB in his MSc. thesis published in 2014. In 2015 JEES were successful under the Wave Energy Scotland NWEC programme and received a research contract valued at £291k to explore the WaveTrain concept in greater depth. The WaveTrain device concept was filed at the UK Intellectual Property Office in the name of Dr Nicolas Wells, JEES, on 8th July 2009.

The Wave Energy Scotland, (WES) research contract covered a series of phases of numerical modelling, experimental tank testing, concept engineering and levelised cost of energy analysis. The Project Team employed during the WES Stage 1 programme included the following teams of specialists:

1. Dr Nick Wells - Project Manager: Joules Energy Efficiency Services Ltd.

2. Dr David Forehand and Dr Jos van't Hoff - Numerical Modelling: The University of Edinburgh
3. Dr Adrian d'Andres and David Crooks - LCOE Studies: The University of Edinburgh
4. Dr Jamie Grimwade and Dr Tom Davey - Tank Testing: FloWave
5. Dr Derek Russell and Mark McConnell - Concept Engineering: RPS Consulting Engineers - Marine Structures Division

The original aims regarding project success covered:

- Scientific Credibility: That the concept operation and performance is demonstrated to be in alignment with scientific and hydrodynamic principles
- Technical Credibility: That there is strong productive interaction with waves in normal conditions.
- Engineering Credibility: That the concept has the potential to be reliable and offers good prospects of being engineered using known techniques and materials. That the concept has the potential to survive in extreme ocean environments.
- Innovation: That the concept is innovative and novel having distinct advantages over existing devices
- Disadvantages: That there is clarity over any disadvantage and there is a credible approach to avoidance or their mitigation.
- Commercialisation Prospects: Long-term LCOE assessment is well informed and convincing showing potential to reach £150/MWh at market maturity.
- Project Design and Deliverability: That the project design is sound and of good quality, and that the proposed main activities are considered and included in a logical manner to meet the project objectives. Also that the project team members are suitably qualified and experienced to deliver the project.

All of these original aims have been addressed during the course of the project with successful demonstration of each item. Perhaps one area of lower success might be attributed to the project management of some aspects of the preliminary tank experimental work to support optimisation studies, where there was a lack of success caused by un-foreseen problems with the calibration and performance suitability of a facility. Lower success was also achieved in the procedure for obtaining consistent scale model applied load damping values.

The measures of project success were developed as deliverables against each of the Work Packages. The Project Outputs and Deliverables associated with the full research contract are summarised in the following Table 1.1.1:

1.2 Description of Project Technology

The key features of the project technology are associated with the geometry of the wave power absorbing bodies and the simplicity of the power take-off system. It has been known for some time that a wedge sliding on an inclined plane is a particularly efficient wave maker. If we reverse time it can also be concluded that the same system is an efficient wave absorber. The WaveTrain WEC utilises this principle through the geometry of the floating absorber which replicates a wedge moving on an inclined plane. In order to extract energy from the incident waves it is necessary to react the mass of the floating wedge against a second large inertia. In this respect a second key feature of the concept is that a constrained mass of sea water is utilised as a very cost effective reaction mass. This sea water is contained within a set of parallel tubes extending at an angle to the free surface below the wedge body. These tubes are open at the bottom end and feed into a common air chamber at the upper end above the free surface. Air trapped in this upper chamber is pressurised and de-pressurised in a cyclic manner by passing waves. Power is extracted from the system through the application of damping on the relative motion between the two bodies through the use of a self-rectifying pneumatic turbine placed in the constricted air flowing into, and out of the chamber. The final novel feature of the WaveTrain WEC is the utilisation of a set of inclined struts linking adjacent members in the array. These struts, when the wedges are placed approximately half a wavelength apart, provide self-reacting support between the adjacent wedges and assist in keeping the floating system moving on a restricted inclined plane. The overall system natural frequency can be adjusted by changing the length of the tubes and the angle of inclination.

Figure 1.2: WaveTrain array suspended prior to immersion in the FloWave tank
(Photograph copyright Joules)

1.3 Scope of Work

The work was divided into several key activities. Firstly, it was appropriate to develop a series of numerical models of the floating sytem with each succeeding model providing a closer representation of the true floating body dynamics. Initially, the dynamics were simplified just to represent a single body moving on a fixed inclined plane with the water column hydrodynamics fully represented. An earlier model had used a point-mass representation of the water columns. The hydrodynamics were modelled using an industry standard package called WAMIT and the water colums were incorporated with lightweight 'lids' as an extra degree of freedom. Subsequently, the models incorporated increasing degrees of freedom to correspond to completely free floating modules utilizing the modelling package 'MatLab' combined with 'Simulink' and 'SimMechanics'. Ultimately, it proved possible to join three floating modules using rigid articulated links to represent the full 3-module array associated with the WaveTrain EWC. The results of specific physical model tests in the FloWave tank were used to calibrate the numerical models so that they provided the closest representation of measured responses. The development of the numerical models was designed to match experimental progress with physical models tested in the wave tank so that the two activities could progress in parallel to improve our understanding of the key WEC characteristics.

Secondly, a series of physical model tests was devised to extract and measure particular characteristics of the WaveTrain WEC including the preferred angle of inclination and separation distance between modules within the array. These preliminary tests were followed with larger 1:35 scale experiments in the industry leading FloWave test facility. The performance of the WEC was accurately measured and charts prepared to illustrate the device relative capture performance. These tests were witnessed by an independent expert verifier. A representative series of wave states was defined by WES and the model was tested in each one to derive the associate rate of captured energy. These results enabled the production of a Power Capture Matrix for the WEC that could be used together with any chosen site wave scatter table to define the overall system power capture at the site.

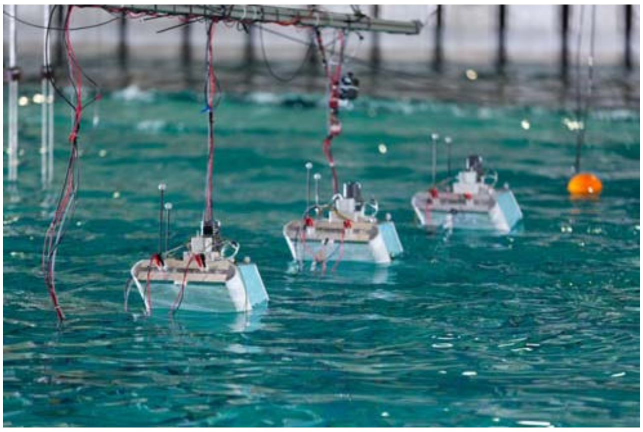

Figure 1.3: WaveTrain power module array during FloWave testing
(Photograph copyright WES)

A programme of Concept Engineering was completed by RPS Consulting Engineers - Marine Structures Division to develop a new full scale preliminary design based upon the use of concrete construction. It was shown that conventional box girder construction techniques could be used to build the water column tubes while the associated wedge canopy structure could be erected using sprayed concrete applied to a steel formwork. Using lightweight aggregate the overall structure could be built at a satisfactory individual unit weight of 750t. The connecting struts and flexible joints can be manufactured in steel with appropriate steel pad-pieces to transfer loads into the concrete structure. The Concept Design utilised a self-rectifying pneumatic turbine for power take-off mounted within a steel duct connected to the canopy air void at the top of the water columns and venting to the rear of the WEC. A mooring design was established utilising conventional catenary cables connected to ground anchors at the seabed and attached to a lead buoy at the front of the linear array of three devices. The WEC swings from the front to line up with the incident waves. Electrical connecting cables follow a conventional arrangement using floats and weights in a loose catenary suspended from the lead buoy to connect to adjacent WEC array members and the seabed.

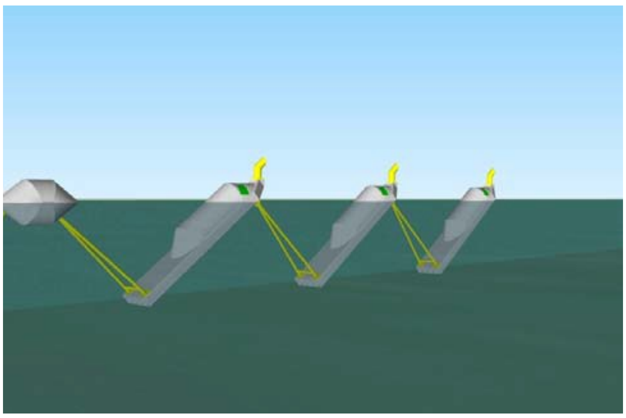

Figure 1.4: WaveTrain Concept Engineering design in concrete

(CAD Image copyright Joules)

Having established the Concept Engineering design it was possible to develop the associated construction, installation and operational costs based upon conventional offshore rates. These costs were fed to the LCOE team based in the University of Edinburgh who utilised them in conjunction with the Power Matrix established from the tank tests and numerical model to develop the levelised cost of energy, LCOE at various sites including the design site offshore South Uist in 100m water depth. It was demonstrated that the design is capable of meeting the 15p/kWh target after the installation of 1GW of WEC devices.

The specification for the work was developed with WES within 11 individual Work Packages:

1. Work Package 1 - Ideas, Analysis, Simulation Optimisation
2. Work Package 2 - Numerical modelling studies
3. Work Package 3 - Building of Tank Test Models
4. Work Package 4 - Variable inclined plane single power module testing
5. Work Package 5 - Fixed optimum angle and damping coefficient array power module testing
6. Work Package 6 - Building of Floating Array Tank Test Models
7. Work Package 7 - Free floating optimum angle and damping coefficient array power module testing
8. Work Package 8 - Standardised performance testing
9. Work Package 9 - Concept Engineering (Inertia Tubes, Canopy, Struts, Flexible Joints, Mooring Arrangements, Assembly and Deployment)
10. Work Package 10 - Costing and LCOE/related metrics
11. Work Package 11 – Completion of design development and Project Management

The milestones and associated deliverables are summarised in the following Table 1.1.1.

WP/Milestone No.	Milestone Title	Outputs (Deliverables)
1	Analytical Optimisation	The optimised WEC design envelope including: 1. Optimum angle of inclination 2. Optimum mass ratio 3. Optimum water plane ratio 4. PTO damping characteristics to enable the tank test models to be constructed. Written report of findings
2	Numerical Modelling Studies	1. WAMIT frequency domain hydrodynamic coefficients 2. Time domain numerical multi-body model of WEC ready for verification against experimental results. 3. Determination of 'q' factor array interactions for the design array separation and inclination parameters. Written report of findings.

3	Completion of tank test models for curved tank tests	Models and sensors delivered to the tank ready for installation, instrumentation calibrated and satisfactory Project Management to Feb 2016
4	Isolated Power Module Curved Tank Tests	Experimental determination for isolated power module of: 1. Optimum damping level 2. Optimum inclination angle 3. Monochromatic CW ratio curve for power module 4. Random wave CW ratio curve Written report of findings
5	Array Power Module Curved Tank Tests 1:80 scale	Experimental determination for isolated power module of: 1. Optimum separation and Monochromatic CW ratio curve for array 2. Optimum random wave CW ratio curve for array and 'q' factor interactions. 3. Peak enhanced random wave CW ratio curve for array and 'q' factor interactions Written report of findings
6	Completion of tank test models for FloWave Tank Tests	Models delivered to the tank ready for installation with instrumentation installed and calibrated.
7	Array Power Module FloWave tank tests 1:50 scale	Experimental determination for 3-power module array of: 1. Monochromatic CW ratio curve for the floating array 2. Random PM wave CW ratio curve for the array and 'q' factor interactions 3. Peak enhanced short crested PM random wave CW ratio curve for the floating array and 'q' factor interactions Written report of findings
8	Standardised Performance Tests	Determination for 3-power module array of: 1. Random wave CW ratio curve for the WEC array for use in the independent LCOE calculations
9	Concept Engineering Phase 1&2	Refined Concept Design for: 1. The Inertia Tubes 2. The Power Module Canopy 3. The Tubular Struts Refined Concept Design for: 1. The Flexible Joints 2. The Ball-Grab connection mechanism 3. The assembly process 4. The deployment process Production of a Confidential Technical Report and Risk Register Analysis against target outcomes
10	Costing and LCOE analysis	The report presenting the independent LCOE and other metrics for the WaveTrain WEC with a target of £150/MWh.
11	Completion of Design and Project Management	Satisfactory completion of the design development process and recording of developments in a Non-confidential summary report

Table 1.1.1: List of deliverables for each work package

1.4 Project Achievements

The most satisfactory outcome from the project was the development of the sophisticated numerical model of the fully floating linked array of three modules. This cutting edge numerical model was developed by the team at the University of Edinburgh in parallel with the programme of physical tank tests which were ultimately used to calibrate the numerical model prior to its use in determining the associated Power Matrix. The only constraint was that there was insufficient time left in the Stage 1 programme to fully utilise the numerical model to optimise the geometry and other key parameters of the design. Conversely, a less satisfactory outcome was achieved from the first two tank tests in the Edinburgh University Curved Tank facility. These experiments could have been more successful in the identification of the optimum angle of inclination for the device and the optimum separation of the modules. The tests were hampered by adverse tank characteristics which masked the results and reduced confidence in indicated outcomes. Thus, the project would have been even better if all of the tank testing had been carried out in the FloWave facility and greater budget had been allocated to the numerical work, with lower costs absorbed by the LCOE analysis. The success of the numerical modelling was entirely due to the high calibre of the individuals performing the analysis and this illustrates the essential need to employ the best researchers in each associated field.

1.5 Summary of Performance against Target Outcome Metrics

The technology of the WaveTrain WEC performed particularly well against the metrics of Performance, Affordability and Availability while not doing quite so well against the metric of Survivability. Each of these performance metrics is discussed separately.

Performance. The top-level objective of an energy capture metric may be defined as the need to measure the energy captured relative to the incident energy while considering the penalty associated with capturing that energy. The key metric is Annual Energy Capture Width defined as the ratio of absorbed wave power (in kW) to the wave resource (in kW/m) assessed at the S. Uist offshore site for a device width of 9.7m. In this respect the WaveTrain WEC performs well generating an Annual Energy Capture Width ratio of 52%. Although the WEC has relatively poor energy absorbed per mass and energy absorbed per surface area because it is comprised of three separate modules with long enclosed water columns resulting in a large surface area and mass. These metrics are contrasted by an exceptionally good ACE value, (the ratio of Average Climate Capture Width and Characteristic Capital Expenditure) of 7.87. The WEC can have a poor energy absorbed per mass value and a high ACE value because the primary construction material is concrete. Thus, although the device has a relatively high mass, the low price per mass of concrete results in an excellent ACE value. The ACE metric is defined as the ratio of Average Climate Capture Width and Characteristic Capital Expenditure which is a proxy for LCOE for low TRL devices used by the US Department of Energy.

Affordability. The overall measure of affordability of an energy generation technology is LCOE and this is directly affected by CAPEX, OPEX, availability, energy-capture and energy-conversion. As illustrated in the previous paragraph the ACE metric provides a good proxy for LCOE for low TRL devices and the WaveTrain WEC has a good ACE metric of 7.87. The use of concrete as a construction material results in relatively low CAPEX. This low CAPEX is accentuated through the use of a relatively simple pneumatic turbine PTO whose slightly lower conversion efficiency is more than outweighed by a low capital cost and high reliability rating associated with a single primary moving part.

Availability. It is generally agreed that there is a direct link between reliability and survivability with both topics being related to the continued ability to deliver grid compliant electricity. Reliability can be defined as the likelihood that a system or sub- system can remain able to deliver grid-compliant electricity for a given period of time during normal expected operating conditions. The development of a metric requires creation of a Failure Modes, Effects and Criticality Analysis, (FMECA). Demonstration in representative conditions is considered to be a confidence generating process and validation activity for the FMECA rather than a success threshold. As for Survivability, the Reliability development process requires creation of a FMECA and generation of confidence in the Mean Time Between Failures (MTBF) predicted by it for all sub- systems and the whole system. In this respect the WaveTrain WEC utilises a relatively simple, one moving part PTO system leading to improvements in MTBF but, conversely the joints and tubular links provide concern with respect to potential structural failure in extreme conditions leading to degradation of the MTBF. It is appropriate to consider measures to off-load the link system in extreme storm conditions to improve the MTBF for these sub-system components. This metric was not developed in detail in Stage 1.

Survivability. Survivability is defined as the ability to continue to deliver grid- compliant electricity after experiencing unexpected or extreme conditions (e.g. extreme wave or sea state). The treatment of survivability is linked to controllability through the possible need to apply controlled survival actions. As for reliability the approach to measuring success in survivability of a device is through the provision of design targets (i.e. survivability wave/climate conditions) and increasing levels of demonstration through the development process to deliver confidence in survivability. This metric was not developed in Stage 1 in any detail. It is recognised that the WaveTrain WEC survivability will be dependent upon the use of controlled techniques to reduce body motions and link loads in extreme conditions. To this end it is proposed to investigate both turbine/generator speed control and device buoyancy volume control techniques in Stage 2 to increase immersion and reduce excitation forces to a sustainable level.

1.6 Communications and Publicity Activity

A deliberate policy of maintaining a low public profile has been maintained to date until such time that the design development has reached a stage whereby it is appropriate to start to raise the project profile. This stage has been reached with the demonstration of very positive initial metrics for the WaveTrain device covering performance and affordability. Much of the cutting-edge numerical modelling work conducted during the first 12 months of the Stage 1 process warrants the production of academic papers and indeed a PhD student Alfred Cotton has been recruited to continue the academic progress in this respect. A new web site at www.jouleswavepower.com has been established to provide a public facing vehicle to provide suitable non-confidential material for use in the public domain. Otherwise, posters and press releases have so far been restricted to those generated by Wave Energy Scotland themselves.

1.7 Recommendations for Further Work

It is vital that time is allowed in a future programme to refine the geometric characteristics of the WaveTrain WEC using an optimisation process based upon the advanced numerical model for the three fully floating power modules within the linear array. There are known to be at least three very important variables that need to be optimised, namely the angle of inclination of the device, the mass ratio between the water in the columns and the rigid body mass and the geometric shape of the wedge section to generate the best hydrodynamic coefficients for ultimate capture efficiency. It would be in-appropriate to forge on with a full scale detailed engineering design until these parameters have been optimised. This optimisation study can be completed at the start of any future programme within 6 months using appropriate expert assistance with the new numerical model. Having identified an optimum geometric arrangement it will be appropriate to confirm the expectations with a series of scale model wave tank experiments to determine the most appropriate load damping characteristics associated with a range of sea states. In parallel with the numerical optimisation process and in recognition of the need to mitigate survival risks it is proposed that investigations should be completed into a volumetric change system to allow greater transparency for the WEC in extreme seas. This will reduce the ultimate loads experienced by the struts and joints and improve their survival capabilities. This physical modification will be coupled to a study on the best control philosophy to adopt for ultimate capture performance and improved survival characteristics.

Having completed the programme to optimise the device geometry it will be appropriate to commence full Engineering Development with programs to address the technical and engineering challenges, availability/reliability issues and survivability while validating affordability though CAPEX/OPEX/LCOE optimisation and reviewing manufacturability, installation, operability and maintainability. It is proposed to continue to employ recognised industry experts with appropriate experience to provide guidance through the various development areas.