Advanced Archimedes Waveswing

WES Novel Wave Energy Converter Stage 2 Project

Public Report

AWS Ocean Energy Ltd

This project has been supported by Wave Energy Scotland

1 Project Introduction

1.1 Overview

The advanced Archimedes Waveswing™ is a submerged heaving point absorber Wave Energy Converter designed for offshore wave energy production and this report provides an overview of work carried out to further investigate the potential of this device. The project work focussed on detailed investigation of possible improvements to the device, further concept engineering, resolution of technical challenges and completion of preparations for a potential partial-scale at-sea prototype deployment. Details of the previous Stage 1 project are provided in report reference nw11_aws_wes-public-report.pdf, available in the WES library (S Grey, June 2017). The Waveswing technology is described in §2 of this report.

1.2 Overall project objectives

The Stage 1 project identified revised configurations which offered potential for significant improvements to the economic performance of the Archimedes Waveswing™ WEC whilst also expected to reduce technical risk. The Stage 2 project objective was to confirm the feasibility of the improved configurations and to prepare for a potential Stage 3 project involving at-sea demonstration of a partial-scale prototype. The specific objectives of the project were to:

- Resolve the technology challenges identified during Stage 1;
- Update concept engineering for new configuration and generate cost estimates based on the revised designs;
- Improve the numerical model for the device and validate against experimental data in order to allow performance optimisation and controller development;
- Conduct performance and survival testing for the revised configuration at model scale;
- Update the LCOE assessment based on revised designs, costs, performance and operational data;
- Prepare for a Stage 3 project including completion of front-end engineering design for a partial scale prototype

The objectives were all met, and the detailed achievements are set out in §4 below.

1.3 Project team

The project was carried out by a broad team over a period of 18 months, with key activities and responsibilities as follows:

Table 1: Project Team

Team member / organisation	Responsibilities
AWS Ocean Energy	Overall project lead and management, technical direction, economic modelling and test site preparatory work.
Quoceant	Key engineering subcontractor with responsibility for concept engineering of FOAK, development of solutions for anchor and tidal

	compensation, support on PTO development and support on partial-scale FEED.
4c Engineering	Lead on partial-scale FEED and support on other subsystem engineering.
Evergreen Innovations	Lead on numerical modelling and tank testing. Metocean and load analysis for partial-scale design.
Wallace Stone	Development of concrete anchor block design.
Pelagic Innovation	Development of survival strategy; Management of risk register and FMEA.
GF Fluid Power	Detailed design of PTO hydraulic circuits.
Steffi Anderson	FEED for electrical power system, power offtake and umbilical.
Trelleborg Ridderk	Review of rolling seal and production of manufacture proposal.
Green Marine	Review of marine deployment / recovery strategy.

The successes achieved during the project demonstrated the value of bringing together a team with such deep understanding and experience of wave power development.

2 Description of Project Technology

2.1 General description

The Archimedes Waveswing™ is a submerged heaving point absorber Wave Energy Converter designed for offshore wave energy production. The system is configured to achieve a very low impedance across a broad wave period range in order to be responsive across typical wave climates. The Waveswing Mk IV system is comprised of four main components

- An inverted canister (the 'Floater') enclosing a volume of gas, that volume having a lower annular free-surface (termed the Annular Water Column (AWC)), said canister being submerged typically to a depth required to achieve 3.0m of clearance to the free surface in its extended (raised) condition. It is free to move vertically, subject to the constraints of a power take-off system, linear guidance and end stop equipment. The crown of the Floater provides the wave absorbing surface;
- An inner telescopic canister (the 'Silo'), concentric with the Floater and comprised of two parts separated by a rolling seal at circa 75% of the diameter of the Floater with the interior being partially evacuated. The upper part of said Silo being connected to the Floater and the lower part of the Silo being restrained by e.g. a mooring system;
- A variable length tether mooring connection, which can compensate for tidal variations, connects the Silo to the Anchor via a suitable quick-release connector; a suitable anchor resists the WEC loading and provides the station keeping capability.

The system is illustrated in Figure 1 overleaf.

2.2 Operating principle

Operation of the Waveswing™ is as follows: At mid-stroke, internal pressures are such that the device is in static equilibrium. An approaching wave crest increases the external pressure on the Floater causing an imbalance in forces and hence the Floater moves downwards causing a further build-up of hydrostatic pressure on the floater surface (i.e. a negative hydrostatic spring response). This is counteracted by the compression of the internal Floater air (the AWC free surface will move downwards as ambient pressure increases), whilst the vacuum chamber volume is also decreased, raising the internal pressure and hence further balancing the external hydrostatic and hydrodynamic forces. The floater continues to compress until the force equilibrium is re-established. The disconnect from a conventional surface piercing hydrostatic spring results in a conveniently soft spring and can achieve a multiplication of the wave height without the need for strong resonant behaviour. The wave is absorbed due to the void created through contraction of the WEC volume, in particular due to the wave radiating potential of the floater surface closest to the free surface. Note also that due to the up-facing orientation of the wave-radiating surface, that diffraction forces on the oscillator are supplementary (and not counter-acting) to wave Froude-Krylov forces. This is another fundamental benefit of the Waveswing configuration over surface piercing oscillators. The process is reversed for a wave trough. The very 'flat' spring curve achieved by this configuration coupled with the low inertia Floater means that the impedance of the device is inherently low, and the response is very broad-banded.

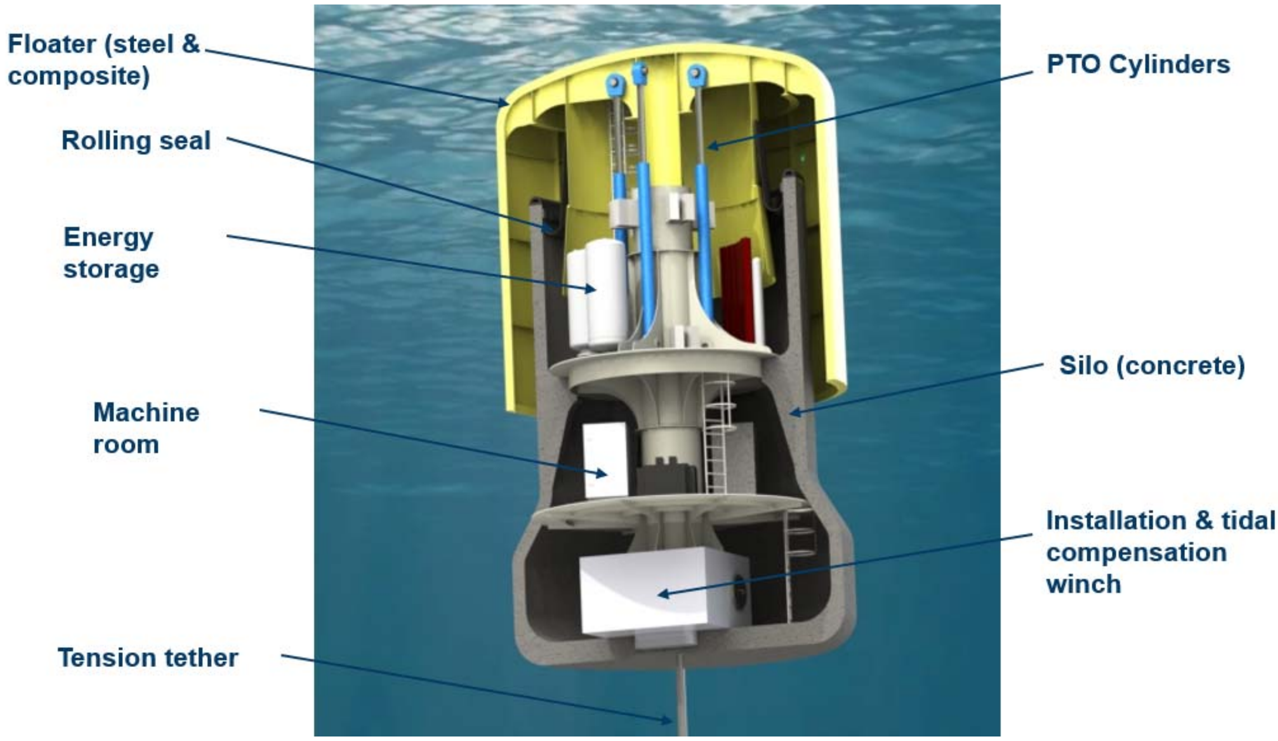

Figure 1: Cut-away of concept design for full-scale Waveswing

2.3 Shut-down and survival

For shut-down or survival the Floater is retracted to bottom-dead-centre where the lower lip of the floater seals against a rim around the silo. The device pitches about the anchor joint in order to shed loads in large waves. Expected loads and pitch motions were investigated using tank testing and numerical modelling and have been previously reported (Spinneken & Tan, November 2017).

2.4 Technology advantages

The major advantages of the Waveswing technology are as follows:

- Survivability – the device has several features that improve survivability including the sub-sea location and ability to achieve mechanical shut-down by removing the differential pressure activation forces;
- Energy capture – the operational principle of the device allows significantly more energy to be captured per unit volume than that which is available from a surface-piercing device;
- Potential for low LCOE – the simple construction, low volume and high energy capture create the necessary conditions to achieve a low levelized cost of energy;
- Very low environmental impact – the high array density, single-point moorings and sub-sea location ensure very low environmental impact and potentially higher stakeholder acceptance;
- Low technology risk – the device has low technology risk due to the simple operating principle and the fact that all sub-systems have been proven in similar applications;

Following this detailed investigation, the project team now believes that the Waveswing offers one of the very best prospects for delivery of affordable energy from the power in ocean waves.

3 Scope of Work

The Stage 2 project was intended to investigate the effects of the technology advances and, in particular, to confirm the potential for projected performance improvement and cost reduction, thus setting a solid foundation for the development programme for the Waveswing™ technology. The scope of work is set out in §0 and detailed fully in the final project report reference 18-107 (S Grey, December 2018). The work breakdown structure main tasks were as follows:

3.1 WP01 Project Management

To deliver the project on time and on budget whilst ensuring all objectives are met.

3.2 WP02 Technology Development & Stage 1 Risk Mitigation

To address the key technology risks identified during the Stage 1 project and to develop the novel sub-systems including seal, PTO, tidal compensation tether and anchor.

3.3 WP03 Engineering Development

To further refine the concept engineering for a full-scale first-of-a-kind (FOAK), confirm all sub-systems as feasible and provide a basis for capex estimation to feed into levelized cost of energy (LCOE) projections.

3.4 WP04 Improvement in Numerical Modelling Simulation Capability

To further improve confidence in the numerical model, in particular improve modelling of the pitch motion of the device and ensure that the control algorithms were correctly represented, all to provide a solid tool-set for future optimisation and engineering work.

3.5 WP05 Model Testing

To provide physical validation of the performance of the revised device configuration and to provide survival loading and motion data for design.

3.6 WP06 Preparation for Stage 3 Partial Scale Prototype

To prepare the ground for a possible Stage 3 project, in particular to produce a project requirements document, select a test site and produce a basis of design for the prototype.

3.7 WP07 Partial Scale Device FEED

To complete the front-end engineering design of a partial scale prototype to inform cost and de-risk the execution of a possible Stage 3 project.

4 Project Achievements

4.1 Main achievements

Overall, the team consider the Stage 2 project to have been a major success in the development of the Waveswing technology. The key objectives as set out in §1.2 were met and progress was made well beyond targets and expectations. In particular, the following represented considerable success points:

1. Identifying a PTO system which is considered capable of meeting all the functional requirements, including peak force capability, controllability and efficiency;
2. Confirming the feasibility of the rolling seal and identifying a development partner who has already built and tested a very similar seal for another WEC;
3. Identifying and front-end engineering a combined installation and tidal compensation system which is robust and effective, thus reducing installation / recovery risks and ensuring that tidal compensation is achieved;
4. Identifying an affordable anchoring solution for early-stage deployments;
5. Identifying feasible engineering solutions for all sub-systems at affordable cost;
6. Validating the time-domain numerical model of the device on a wave-by-wave basis, thus enabling the team to investigate strategies for further power production increases;
7. Achieving better than three-fold increase in power from the Waveswing as compared to Stage 1 results when normalised to floater area;
8. Confirming the feasibility of the installation / recovery operations in sea-states up to Hs 2.0m, thus reducing weather delays in maintenance and improving availability estimates to above target levels;
9. Confirming that the revised configuration is likely to be able to deliver energy at a cost below £150/MWh after 1GW of cumulative installed capacity;
10. Completing the front-end engineering design and planning for a Stage 3 project which will deliver significant benefit to the Waveswing development programme and presents a major success opportunity for the WES NWEC programme;

4.2 Lessons learned

In terms of lessons learned, these were many but included the following main points;

<u>Design process and timescales</u>

- The project set an ambitious work programme and completion within the time and budget available was challenging. This put pressure on some of the design processes and as a result some inconsistencies crept in. Whilst these were minor in nature, they nonetheless reflected the importance of rigorous systems engineering procedures and design process control;
- It is the nature of R & D that design iterations will be required. The tight project timescale and linear programme did not allow for design iterations (e.g. after the CDR) and hence some aspects of the design were not fully closed out as we would have wished;

Device performance

- The Waveswing possesses a unique operating principle that allows it to exceed the performance of surface-piercing point-absorbers by a factor of 2. This was amply demonstrated through the excellent performance which approached 70% of the theoretical point absorber limit in some sea-states.
- Device performance is critically dependant on control and hence it is extremely important to ensure that the PTO is capable of providing the control responses demanded in all conditions.
- Linked to the previous point, the traditional approach of tuning the physical aspect of the device to provide resonance in the most energetic sea-states was not found to be important. Rather, 'base' device tuning to a higher frequency was found to be more helpful as this assisted rapid control responses.

Device configuration and engineering

- A hydraulic PTO is capable of providing all of the required control capability, whilst also providing a cost-effective means of achieving peak force and smoothed power. At present, there does not appear to be a viable alternative to a hydraulic system.
- The rolling seal has previously been developed and used in many industrial applications. A similar seal has been built and tested for an alternative WEC design.
- Providing anchoring at an affordable cost remains a challenge and is likely to be a key cost driver in the future.

Overall

The Archimedes Waveswing MK IV appears to offer significant potential for competitive production of renewable energy in the medium term. The remaining technical challenges appear capable of being met and the next step should be to design, build, test and deploy a half-scale device in real sea conditions.

5 Summary of Performance against Target Outcome Metrics

5.1 Performance against target metrics

Overall performance against the target metrics set at the entry to the Stage 2 project was good with the following specific metrics being achieved:

- Capex of less than £8,800 for a first-of-a-kind (FOAK) pre-commercial machine was met after one round of engineering optimisation, notably reducing structural volume and optimising anchor loadings;
- Opex of less than £280/MWh for a FOAK was met easily with estimated costs being around 1/3 of the target value;
- Rated capacity of at least 160kW was met with the FOAK being rated at 195kW and a development pathway to 250kW being easily achieved without increase in device scale;
- Conversion efficiency of at least 70% appears to be achievable as evidenced by operational data for the Pelamis P2 PTO on which the Waveswing system will be based;
- Survivability metrics are difficult to quantify as survival is a fundamental requirement, however analysis and expert review indicate that device survivability will be high;
- Device availability is expected to exceed 95% in a full-field deployment scenario;
- The device is scale-able to 500kW as a single device and is capable of being combined with other Waveswing devices onto a single sub-sea structure to produce a multi-MW generation platform;

Detailed evidence for the above is provided within the various project reports which whilst confidential may be released to interested parties under NDA following agreement with AWS Ocean Energy Ltd.

6 Recommendations for Further Work

This Stage 2 project resulted in all sub-systems being advanced to TRL 4 or beyond. Accordingly, the next step in the development process will be the design and construction of a partial-scale prototype for real-sea deployment. It is anticipated that this will be completed under a WES-funded Stage 3 project. The work required under such a project will be split into two workstreams, namely technology development and demonstration and test. The scope of each is described below:

6.1 Key technology development workstreams

The technology development workstream will focus on reducing technical risk in novel sub-systems. The key areas of focus will be:

- Optimisation of structure for cost and survivability
- Development of Waveswing-specific PTO based on Quantor hardware
- Development and testing of rolling seal

6.2 Key demonstration and test workstreams

The demonstration and test workstream will focus on reducing uncertainty through demonstration of systems in an operational environment. This is a key requirement for technology qualification and advancement to TRL6 and beyond. The following activities are recommended:

- Demonstration of installation and removal operations
- Prove survival systems and survivability
- Prove the PTO and control system and replicate tank-scale power capture and control at large scale and in a real-world environment;
- Investigate the wider control of the device, particularly internal air pressure control and confirm stability;
- Demonstrate operation of tidal compensation system;
- Investigate environmental effects, biofouling, etc to inform full-scale design;
- Collect load and motion data to inform and de-risk full-scale design

7 Communications and Publicity Activity

During the course of the project the team has been focused on the technical aspects of the work. Accordingly, communications and public engagement has been limited to participation in the WES annual conference and presentation of a paper at the Marine Energy Technology Symposium in Washington DC in April 2018.

8 References

The following reports have been referenced within the body of this report. These reports are confidential but may be released to bona-fide interested parties under NDA and subject to agreement of WES and AWS Ocean Energy Ltd.

Quoceant. (January 2018). *18-002r0 Waveswing IV Concept Engineering Design Report.*

S Grey. (December 2018). *18-107 Confidential Technical Close-out Report.* AWS.

S Grey. (June 2017). *nw11_aws_wes-public-report.pdf.* WES.

Spinneken, J., & Tan, W. (November 2017). *17-034 Test report for extreme sea states testing (1:40 model).*