Anaconda Novel Wave Energy Converter

WES Novel Wave Energy Converter
Stage 1 Project
Project Report

Checkmate Seaenergy

This project has been supported by Wave Energy Scotland

1 Project Outputs

1.1 Project Introduction

Checkmate Seaenergy Limited (CSL) is developing a wave energy conversion (WEC) device, the Anaconda. Anaconda is a radically new approach to wave energy conversion. In essence, it is a long water filled flexible rubber tube floating just beneath the sea surface and aligned in the direction of wave travel, with a power generating turbine at the stern (Figure 1). As a wave passes, the tube flexes due to varying pressures in the sea causing a "bulge" wave to propagate down the tube's length, gathering energy from the sea wave as it goes. The bulge wave propagates at a speed determined by the mechanical properties of the rubber tube. Continuous energy gathering results from careful design of the system, matching a resonance between the bulge wave and the incident sea wave. Energy from the sea wave is stored in the tube as the bulge wave grows and stretches the rubber. The bulge wave travels just in front of the wave rather like a surfer, picking up energy as it progressively increases in size. A closed loop power take off (PTO) at the stern of the tube then temporarily stores these bulges of energy and converts them to electrical power by flowing through a turbine between a high pressure and a low pressure accumulator.

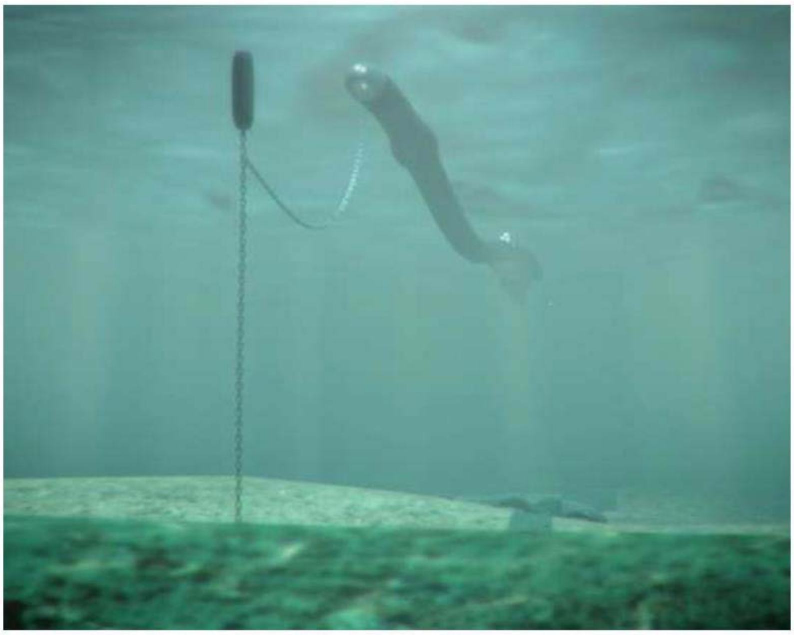

Figure 1: Anaconda Wave Energy Converter in a proposed installation configuration (sub-surface view).

Wave Energy Scotland (WES) has awarded Anaconda funding to progress the development of this and other novel WECs through a series of performance characterisation tank testing, concept engineering and numerical modelling activities. WES has been set up to facilitate developers to achieve a level of readiness where large scale utilities and investors feel comfortable stepping in to support the technology development process. To achieve this level of maturity, devices must show a development path that can achieve a Levelised Cost of Energy (LCOE) of £150/MWh. This project was intended to address this challenge for the Anaconda technology by optimally configuring the technology to balance between power performance, survivability and cost effectiveness of such a novel system to generate electricity at utility scale.

CSL is a world leading wave energy technology developer who has carried out an early stage technology development plan over the past c. 8 years. CSL contracted three different sub-contractors to manage and perform some of the work in this project (Figure 2). CSL managed the commercial aspects of the project, provided technical overview and contributed the vast experience gained to date with the model testing and model building of the Anaconda technology. Black & Veatch were responsible for the overall technical project management of the project, as well as concept engineering, life cycle cost assessment and third party verification (TPV). Strathclyde University were in charge of the tank testing, while INNOSEA were responsible for completing the numerical modelling scope.

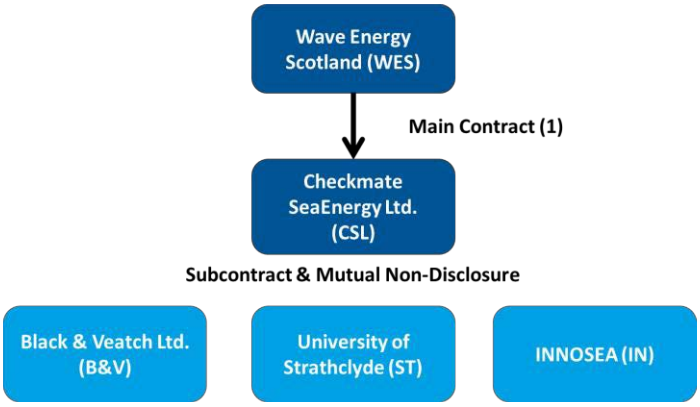

Figure 2: Commercial Structure

1.2 Description of Project Technology

The Anaconda technology is based on the propagation of internal bulge-waves through a flexible tube. The tube is intended to sit just below the water surface and is aligned perpendicular to the oncoming wave front. The dynamic pressure variations applied to the flexible bow of the tube by incident ocean waves change the cross-section of the tube at frequencies which initiate an internal bulge-wave, which then propagates inside the tube in phase with the external ocean wave. The bulge-wave continues to extract energy from the external ocean wave as it propagates towards the stern PTO. The speed of the bulge propagation along the tube is determined by the distensibility of the tube and is the key parameter in tuning the bulge-wave tube to the oncoming wave resource. If this speed is close to the phase velocity of the waves, then there is a resonance between the two and optimised energy transfer between the two. Distensibility is the capability of stretching or swelling of the tube and defined as a function of tube working diameter, thickness, percentage of rubber to inextensible material in the circumference and Young's Modulus of materials. The bulge-wave technology is a closed-loop system, i.e. there is a set volume of water within the tube and accumulators which provide a mean internal tube pressure. The working pressure also allows some control over the tube distensibility.

The Anaconda technology embodies a complex hydro-elastic problem directly coupling power performance and survivability in both extreme conditions and fatigue conditions as a result of millions of duty cycles during operational conditions. The governing design parameters of the bulge-wave tube's dynamic response to wave excitation influence this balance between cost, power performance and survivability. Determining how to select the particular design parameters to address this balance and demonstrate economic potential was a key target outcome of this project. The project aimed to use laboratory and computational analysis to give confidence in the overall technical and economic feasibility in line with WES objectives, paving the way for further development towards implementing a prototype system.

In order to transfer the absorbed mechanical energy in the bulge-wave to electrical energy, a PTO system is required at the stern of the tube. To enable this, the high pressure bulge induces flow into a high pressure accumulator through an array of check valves. The flow is then directed through a hydro-turbine into a low pressure accumulator, with relatively smooth power delivery due to the storage capacity in both accumulators. The generation cycle is completed when the pressure in the bulge-wave tube stern drops below that of the low pressure accumulator.

The Anaconda may be regarded as radically different in its approach to extraction of wave energy and the reasons for this may be summarised in two points:

1. It uses bulge-wave hydrodynamics to extract energy from ocean waves which is a unique concept in the industry; and,

2. It uses flexible materials to achieve this resulting in no rigid articulated joints thus avoiding any issues with significant point loads from actuators or end stop failures.

The use of a wave absorbing mode based on flexible materials is a radical change from other families of WEC devices, with potential for step-change improvements in areas that impact overall LCOE:

- A self-referencing absorber based on flexible materials avoids the need for any articulated joints, reference bodies and/or end stops associated with rigid wave activated bodies. This offers potential step changes in reliability and survivability.

- The inflated structure permits the use of new installation and maintenance principles for marine operations offering potentially radical changes to installation and O&M costs.

- The bulge-wave principle for converting wave energy is entirely novel and has been patented by CSL. While impressive energy production has been measured experimentally, the full energy production potential is only just beginning to be understood.

- There is a step change in structural weights and material costs.

- There is a drastic reduction in the criticality of structural failure modes relative to large steel structural failures.

The Anaconda technology provides a range of improvements to the status quo for attenuator systems and represents one of the most significant step changes in marine energy technology. While quantifying and realising these improvements in practice presents a range of challenges in itself, engineering solutions do exist to meet these challenges.

The novelty of the Anaconda technology presents substantial opportunities to reduce LCOE of wave energy technology due to the current projected low CAPEX, but also through the significant amount of learning which can be achieved during the continued development and understanding of this concept. This is in contrast to rigid body structures where there are well-established analysis, design and construction techniques but often more limited learning potential in delivering on a pathway to the WES target unit cost of energy.

Within the economic justification for the Anaconda technology, there is a unique treatment of the design life of the primary converter as a system component throughout the lifetime of a commercial array. Due to the fatigue characteristics of the tube structural configuration and the capital costs of the tube in isolation, it is feasible (to WES targets) to treat this component as a replaceable component. This is very different to the approach taken to steel primary converters.

1.3 Scope of Work

The fundamental performance and concept verification of the bulge wave tube has been carried out by CSL in previous tank testing campaigns at Haslar and the Kelvin Hydrolab. These tests validated the underlying bulge-wave principal. However, the commercial viability of the bulge-wave Anaconda concept is dependent on a thorough understanding of and engineering balance between power performance and survivability which are inherently coupled through a complex hydro-elastic problem. The principal learning objective for this project was to address this issue while demonstrating the potential for step change improvement in LCoE relative to the best-in-class attenuator. The Anaconda technology configuration assessment metrics include:

- Non-dimensional hydrodynamic power absorption performance;
- System CAPEX;
- LCoE – which captures the effects of all of the above and was the ultimate metric applied to assess viability against the WES criteria.

The output was a detailed configuration description (addressing the integration and system uncertainties) and an assessment of LCOE potential, ready for stage 2 developments. This was achieved through the following key work streams:

1. System Characterisation – identification of the baseline Anaconda technology concept based on previous work. Based on previous work which proved the fundamentals of the bulge wave concept, a hypothesis on how distensibility may control performance and resilience was developed and a baseline Anaconda technology concept was developed which preliminarily optimised the balance between power performance and survivability. Four survival strategies were also conceived as options with potential to address resilience to extreme events. The reference site proposed for this project was South Uist, Scotland. This was used to define survival wave load cases and to assess the performance potential. Prior to tank testing, analytical models of baseline power performance were used to inform a preliminary cost-benefit analysis on the various potential configurations. This information was used to establish the test programme for the WES project and also to target the development work required to validate the approach.

2. Small Scale Hydrodynamic Model Testing – tank testing of the baseline Anaconda technology concept with mooring system adhering to Equimar standards at a scale of c. 1:25. The testing was based on 2 objectives:

    a. Exploratory testing to understand the efficacy of different tube design parameters and their effect on material strain and performance. The testing would also aid understanding of potential survivability strategies.

    b. Final performance testing across the operating regime, which characterised the performance of a final configuration to WES requirements. A full performance test had not been completed for the Anaconda concept to date. This performance test was third party validated.

3. Numerical Modelling – due to the complex nature of the bulge-wave concept, no numerical modelling capability currently exists in a suitable format for use within this project. However, CSL recognised the importance of having such a design tool available for later stages for site specific designs. Therefore, a framework for the development of a suitable numerical modelling tool was produced by Innosea. This framework provides the foundation from which a numerical model design tool may be produced in Stage 2 to assist in future developments and detailed design work.

4. Concept Engineering – This work package was required to interpret the tank testing results and assess the technical feasibility and likely characteristics of an economically refined Anaconda configuration. An assessment was carried out addressing the effects of key parameters on both cost and performance. A probabilised cost breakdown of all subsystems and balance of plant was developed for a system that meets fatigue and extreme survivability criteria, while maintaining target performance levels. This iterative process led to definition of the characteristics of the most economically advantageous structural configuration as well as giving confidence that resilience criteria can be met without adopting additional survivability strategies.

5. Life Cycle Cost Assessment (LCCA) – Whilst the concept engineering addressed the technical feasibility of the Anaconda technology concept, a life cycle cost assessment was carried out to quantify the economic potential of the technology. This included a detailed CAPEX assessment of the adopted structural configuration including the mooring system and balance of plant. This process included an uncertainty analysis as most major input factors are described by a probability density function (PDF). A probabilistic time domain O&M model was used to assess a farm scenario at the reference site including the availability impacts of a "hot swop" O&M strategy. The LCCA study investigated a near term solution which could feasibly be deployed in the 2020's and a longer term solution incorporating new materials and using credible learning rates for power performance and certain cost elements.

The basic project processes described above were in accordance with WES issued guidance documentation and represent industry best practice in the development of early stage WEC technology. The target outcome metrics expected from this project can be incorporated into the LCoE approach adopted, together with full project lifecycle economics.

1.4 Project Achievements

The project team was able to deliver the entire scope of work submitting the necessary documents on schedule. The primary objective of this project was to ensure that a sufficient understanding of the Anaconda hydro-elastic problem and its impact on LCoE and resilience was gained before progressing to the next stage of development. The project successfully built on knowledge gained to date and applied industry best practice and expertise in tank testing, numerical modelling and structural analysis in order to allow completion of a further 'optimised' design iteration. This now takes into account essential survivability and lifecycle cost constraints to reflect the full scale realisation of the Anaconda technology. This puts the technology on a credible commercial pathway to deliver on target outcome metrics (Section 1.5) and firmly within the WES Novel WEC staged process.

The economic potential is based primarily on the experimentally measured performance levels of the scale model since no reliable numerical extrapolation of results is possible for the novel system. This is the measured hydraulic power input to the turbine location, net of experimental scale losses such as rubber hysteresis, PTO impedance characteristics, and hydraulic losses in check valves and pipework, all of which are likely to be improved under future developments to full scale. Numerous opportunities were identified to improve future performance in the shorter term, which will be the focus of plans for further baseline concept refinement in Stage 2. In the long term, opportunities such as the potential for alternative novel PTO technology and improved control provide the opportunity to deliver long term WES LCOE targets.

Whilst the above achievements are significant, extensive exploration and optimisation of Anaconda performance remains challenging. There is significant novelty in the fundamental tube physics which affords the means to more rapidly deliver fundamental step changes in wave energy conversion performance. However, the methods to explore design options for such a complex hydroelastic system, leading to the optimum tube response to waves are not yet well developed. This applies both experimentally and numerically:

- The lack of an established and verified analytical or numerical method that fully describes the physics required to extrapolate performance and induced loads means that there is a strong dependence on experimentally measured power performance and a limited opportunity to optimise the design with analytical and numerical tools.
- The difficulty in producing repeatable performance results from one tube to the next due to manufacturing variability at experimental scale means there is incomplete control over the design of experiments.
- A means to test several tube design parameters by applying an alternative OWC type PTO that facilitated more rapid swapping of the tubes was not successful on testing. This resulted in some lost time and an ongoing dependence on the more robust accumulator PTO design, which works reliably on test. However, this design requires careful set-up such that the PTO is designed to match particular tube design pressures and the time taken to swap tubes restricts the number of design points that can realistically be tested during experimental campaigns. The impedance characteristics of the PTO, potential loss mechanisms and the degree to which they may be detracting from measured power potential are also not yet well understood.

The team’s principle achievement is in acknowledging and addressing these challenges in building on a significant body of experimental data collected over many years. The project has succeeded in validating an Mk1 Anaconda configuration that is technically feasible and ready for Stage 2 development, while a credible path to deliver on WES economic objectives is also established.

1.5 Summary of Performance against Target Outcome Metrics

The preliminary LCCA assessment has identified the critical CAPEX components of the Anaconda system and estimates of the OPEX costs for the technology. A probabilistic LCOE assessment has

been carried out for the Anaconda technology for two specific scenarios including a pre-commercial 6MW array and commercial 100 MW array.

The assessment has suggested that the Anaconda technology would be able to meet the WES target of £150/MWh for large commercial arrays which forms a reduction of c.30% on preliminary LCOE projections. This reduction has been made possible through the tank testing and concept engineering work packages. The work has increased confidence that acceptable fatigue life can be affordably achieved and a much better understanding of what drives the baseline performance has been achieved. The work also identifies several specific opportunities to improve performance, which also justify stronger performance learning rate projections.

All of these aspects are captured in the probabilised LCOE assessment of the technology. Some key aspects which have contributed to further reductions in LCOE include:

1. Implementation of a 'hot-swop' O&M strategy which ensures that high array availability can be maintained with a defined number of hot-swop machines available to facilitate this strategy.

2. More certainty on designing to deliver the fatigue life of the bulge-wave tube and service intervals. The current projections may be conservative with the application of a Design Fatigue Factor (DFF) of 3 as for general offshore structures. As the tube is not part of a primary structure in terms of device integrity, commercial risk appetite may permit the DFF to be reduced to 1, if technical configurations of the device can ensure the overall risk profile meets expectations of codes like IEC62600-2. Irrespective, less conservative life projections will further reduce the number of expected device interventions currently modelled.

3. Tube replacement following a fatigue failure is now replaced with a repair cost and operation as it is expected that fatigue failures will be sited at localised details, i.e. joints at rubber-steel interfaces etc., and that these can be repaired while overall structural strength is retained.

4. Increased PTO efficiency assumed due to the ability to match the smoothed flow with the optimal operating point of a low-head hydro turbine.

The Anaconda WEC is a truly novel concept in wave energy and the work completed by the team in engineering and economics highlight the prospects for the concept and its ability to reach the commerciality targets as set out by WES at £150/MWh.

1.6 Communications and Publicity Activity

Prior to participation in the WES Novel WEC programme the Anaconda WEC had been under development by CSL since 2009. Throughout the time of that development CSL had actively sought private investment and had consequently promoted its activities to potential investors. This had taken the form of press releases and regular updating of the CSL website: http://www.checkmateukseaenergy.com/. Since the development at that time had centred on performance testing at 1:25 scale, several investors witnessed tank tests at various UK test facilities. CSL had also invited a limited number of journalists to witness tests which had resulted in coverage in mainstream media, for example this BBC coverage in 2009: http://news.bbc.co.uk/2/hi/science/nature/8034884.stm and this coverage in the Guardian at about the same time: https://www.theguardian.com/environment/2009/may/06/anaconda-wave-power.

Anaconda was also the subject of an interview with Des Crampton on the BBC's Today Programme in April 2009.

CSL had participated in the Carbon Trust's Marine Energy Challenge which resulted in the project receiving funding under their Marine Energy Accelerator programme over the period 2009 to 2011 and during that time had enjoyed the benefit of publicity material prepared by Carbon Trust. Anaconda is mentioned in a case study in the final report on the Marine Energy Accelerator which can be seen at: https://www.carbontrust.com/media/5675/ctc797.pdf.

CSL had also promoted research at Southampton University which had itself generally publicised their work as can be seen here: http://www.energy.soton.ac.uk/anaconda-wave-energy-converter-concept/. Professor John Chaplin of the University had jointly published several papers on Anaconda with the inventors, all of which are cited at section 1.8 of this report.

CSL commissioned a major rubber fatigue study with the Tun Abdaul Razzak Research Centre (TARRC), the research arm of the Malaysian Rubber Board which also served as the doctoral thesis of an employee at Southampton University. TARRC publicised this work in their house journal in February 2012: http://www.tarrc.co.uk/pages/Anacondaprojecttesting.htm. A paper based on the thesis was independently published and can also be found at: http://eprints.soton.ac.uk/399288/7/evaluation-of-rubber-compounds-for-the-development-of-wave-energy-converter-%20%20%20Journal.pdf.

1.7 Recommendations for Further Work

The key recommendations for further work to continue developing the Anaconda technology in accordance with WES guidance include:

- Further tank testing at small and large scale to further explore the design space in the region of interest highlighted through Stage 1 work. Testing will focus on engineering aspects to guide the design of the full scale prototype and small sea-going prototype as well as reduce the remaining uncertainty in scaled tube performance, by testing larger tubes at a scale of c. 1:10. This will also include the impact of variable rubber compound impacts and hysteresis.
- Further design works on the baseline configuration of the Anaconda WEC primarily on local structural details to assess resilience in fatigue and ultimate loading conditions.
- Further detailed analysis of the PTO interface with the bulge-wave tube to develop and refine the functional requirements of the PTO system and to improve power performance overall.
- Delivery of the numerical modelling framework and a parallel experimental validation exercise that will seek to apply a more novel and controllable experimental scale PTO interface such that the numerical modelling tool validated and an understanding of the full wave absorption potential can begin to be developed.

These proposed activities align with the WES expectations on Stage 2 development work and the team is currently developing a detailed work plan to deliver this.