Wave Energy Transmission Module

WES Power Take Off Stage 2
Public Report

Romax Technology Ltd

This project has been supported by Wave Energy Scotland

Project Introduction

Romax Technology, Sea Power Ltd and Limerick Wave Ltd have been awarded Stage 2 funding by Wave Energy Scotland (WES) to carry out continuing development and scale testing of their concept for a geared power take-off (PTO) for a wave energy converter (WEC). This follows the successful delivery of a Stage 1 project in which the feasibility of achieving a good energy output from a WEC using a PTO comprising a two-stage planetary speed-increasing gearbox coupled to a generator (referred to here as the 'baseline' layout) was demonstrated through concept design and simulation.

The Stage 2 project has investigated the potential of using more advanced mechanical layouts in the gearbox to further improve both the quantity and quality of electrical output. A small-scale test rig was designed and built, and fitted with scale representations of the mechanical layouts to be considered, adjusted to reflect the dynamic characteristics of the full-scale concepts. Following development work on the test rig, the PTO layouts were fitted to the scale model SeaPower Platform and tested at FloWave Test Tank in Edinburgh.

Romax Technology Ltd, based in Nottingham, UK, are world leaders in the design and simulation of mechanical and electro-mechanical drivetrain systems, with a particularly strong track record in providing turn-key design solutions, consultancy services, condition monitoring and field services to the wind energy industry globally. SeaPower Ltd, based in Enniscrone, Republic of Ireland, are an Irish R&D company whose founders have been pioneers in wave energy development since 1990. They are the developers of the SeaPower Platform. Limerick Wave Ltd are IP holders for one of the novel gearbox layouts assessed as part of this project. They have previously developed a test rig with SeaPower Ltd to demonstrate their concept.

Description of Project Technology

The core technology is a multi-stage, speed-increasing gearbox connecting the WEC prime mover to a permanent magnet generator. The layout is similar to a modern, 'medium-speed' wind turbine drivetrain. The key advantages of this technology are its extremely high transmission efficiency and ability to take advantage of the highly cost-competitive global supply chain which already exists to supply similar products to the wind energy industry.

The use of a gearbox to increase the rotation speed permits the generator to be significantly smaller than one directly driven by the prime mover. For a WEC of similar scale to the Sea Power platform, it is unlikely that a directly driven generator could practically be manufactured, given the extreme torque capacity required. Even for smaller WECs, the reduction in generator cost is expected to more than outweigh the cost of the gearbox.
A geared transmission is considerably more efficient than a hydraulic transmission, with transmission efficiencies of greater than 97% (from prime mover to generator) typical in wind turbine applications. Crucially for the WEC application, the efficiency does not vary significantly with part-load operation.

The proposed layout permits both gearbox and generator to be contained within a single robust, well-sealed

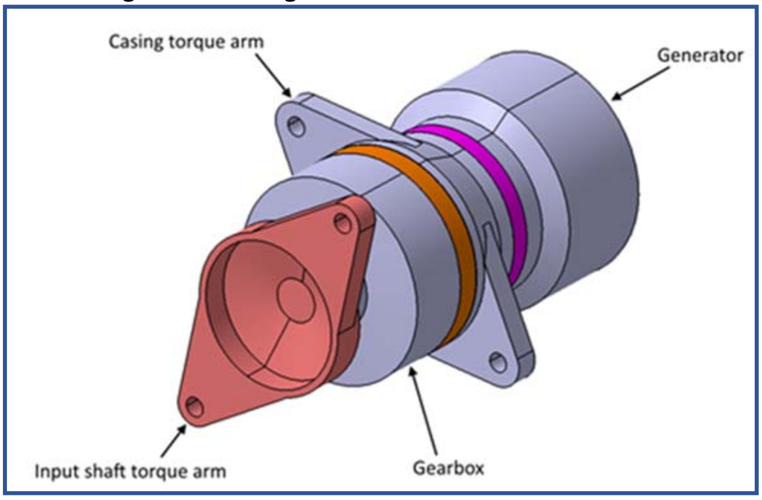

Figure 1: Full-scale PTO concept

housing. There is only one rotating seal in the whole design, where the input shaft enters the gearbox. The shaft arrangement and size is compatible with mature marine propeller shaft sealing technology, which is well-proven for extended lifetimes and permits fully submerged operation (essential for oscillating wave surge converter type devices). The PTO layout has no limitations on travel (and in fact could be continuously driven through complete rotations). This means there are no requirements for end stops to be incorporated into the WEC to protect the PTO, and it is able to survive (and indeed continue to generate power in) the highest sea states.

Scope of Work

In addition to the baseline layout from stage 1, 2 alternate mechanical transmissions were considered to demonstrate viability/potential of improving the quality and quantity of output. The following are three different transmission layouts that were investigated in stage 2:

- Baseline – Multi-stage, fixed-ratio planetary speed-increasing gearbox

- Differential – Dual-output/variable ratio transmission using planetary differential
- Rectifying – Mechanical rectification/freewheeling using one-way clutches

The key activities undertaken in stage 2 are shown below in Figure 2:

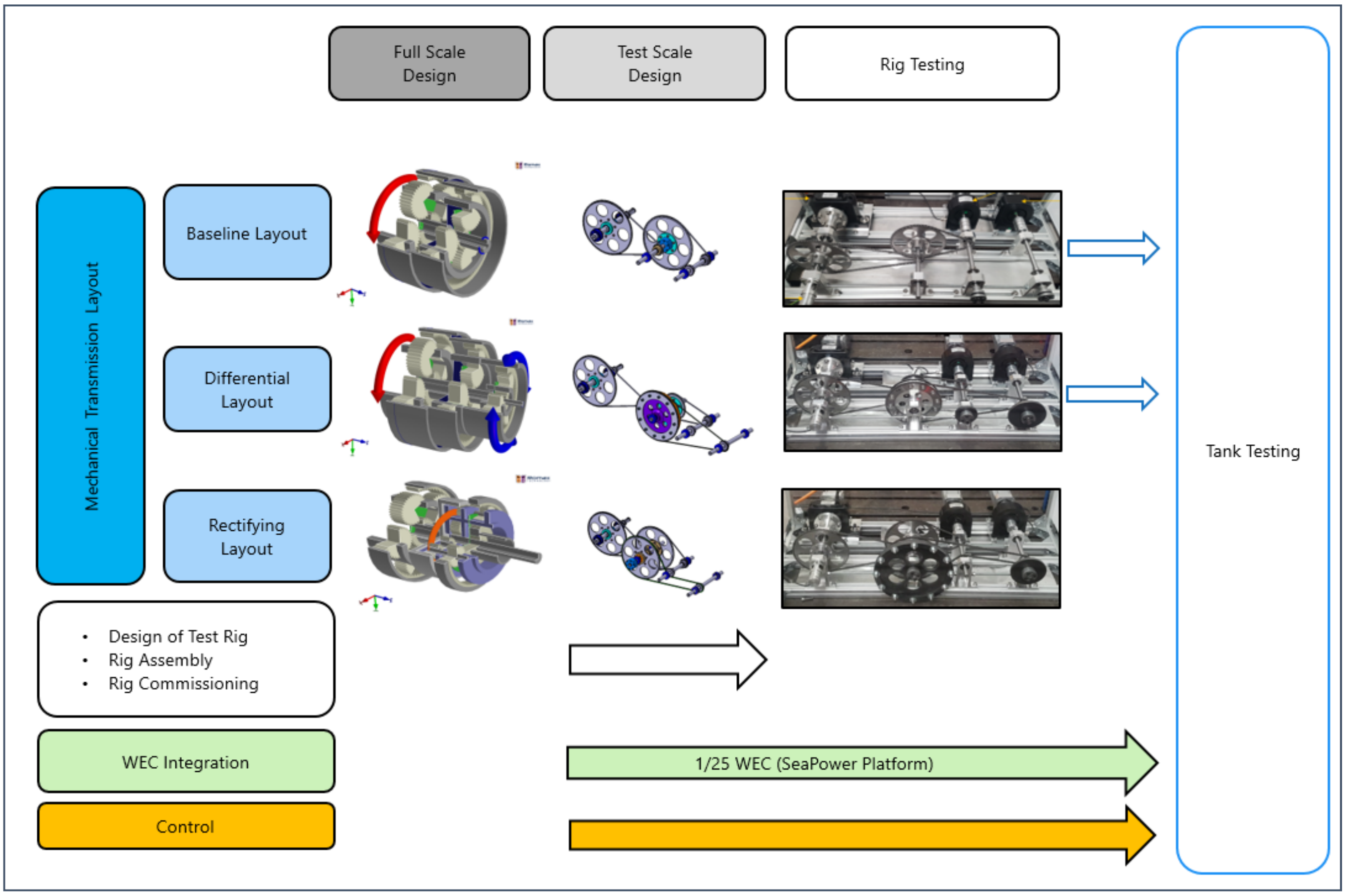

Figure 2: Key Activities in Stage 2

The main aim and reasoning for each key activity are described below in Table 1:

Table 1: Key Activity Description

Key Activity	Description
Full Scale Design	The aim of this activity was to produce a concept design of each of the advanced layouts at full-scale which is sufficiently developed to estimate the dynamic characteristics of that layout. This information was used to ensure that the small-scale representations of each layout replicated the behaviour of the full-scale system and thus that the results of testing could reasonably be used in estimating the cost of energy of a future commercial product.
Test Scale Design	The aim of this activity was to design small-scale representations of each of the three layouts (baseline plus two advanced layouts). For each layout, the small-scale was designed to reproduce as faithfully as possible the kinematic (relative motions, speeds, directions) and dynamic (scaled inertia referred to the WEC) behaviour of the full-scale systems, at a size suitable for bench and tank testing.
Rig Design, Assembly and Commissioning	The aim of this activity was to design a highly flexible 1/25 scale test rig which could deliver appropriate loading and motion derived from WEC damping strategies and wave inputs considered in Stage 1. This included the physical structure of the rig, the power sources and sinks, and the control system hardware and initial software development.
Rig Testing	The aim of this activity was to fully characterise each PTO configuration, including verifying that target inertia values had been achieved, and to bring each control system to a level of development maturity where the potential of the configuration could be assessed. At the end of this phase, the decision was made to carry the differential and baseline layouts through to tank testing.
Tank Testing	The aim of this activity was to validate simulation and test rig findings against real WEC behaviour for the baseline and differential configurations, enabling improved LCoE estimates and supporting decision on direction for Stage 3.

Project Achievements

During this project, an extensive investigation has been carried out into the potential of two alternate mechanical configurations to achieve an improvement in the quality and quantity of energy capture relative to the 'baseline' fixed-ratio speed-increasing gearbox.

This has been carried out by the design and manufacture of small-scale 'representative PTO systems' along with a highly flexible test rig as shown below in Figure 3. As well as allowing the three layouts of interest to this project to be tested, this rig can be reconfigured to test any future mechanical configuration which may become apparent – particularly in the context of applying the core technology to alternate WEC types. There is scope for future enhancement of the rig to incorporate WEC simulation in the input motion control side to provide more realistic response to applied PTO loads.

Figure 3: 1/25 scale PTO Test Rig at Romax Testing Facility

The project has demonstrated that the inertial characteristics of the scale PTOs could be adjusted to match a (suitably scaled) full-scale system. Mechanical losses in the test systems were, as expected, proportionally higher than would be expected in the full-scale systems, which does require consideration in processing the results.

As well as characterising the mechanical systems, the rig testing was used to develop the necessary control strategies and implement them into a prototype control system. In carrying out this project, a great deal has been learnt by the consortium about the requirements for effective control of the gearbox/generator PTO system when fitted to the WEC.

Following completion of rig testing, the representative PTOs were integrated into the 1/25 SeaPower Platform and a programme of tank testing was conducted at the FloWave test tank as shown below in Figure 4.

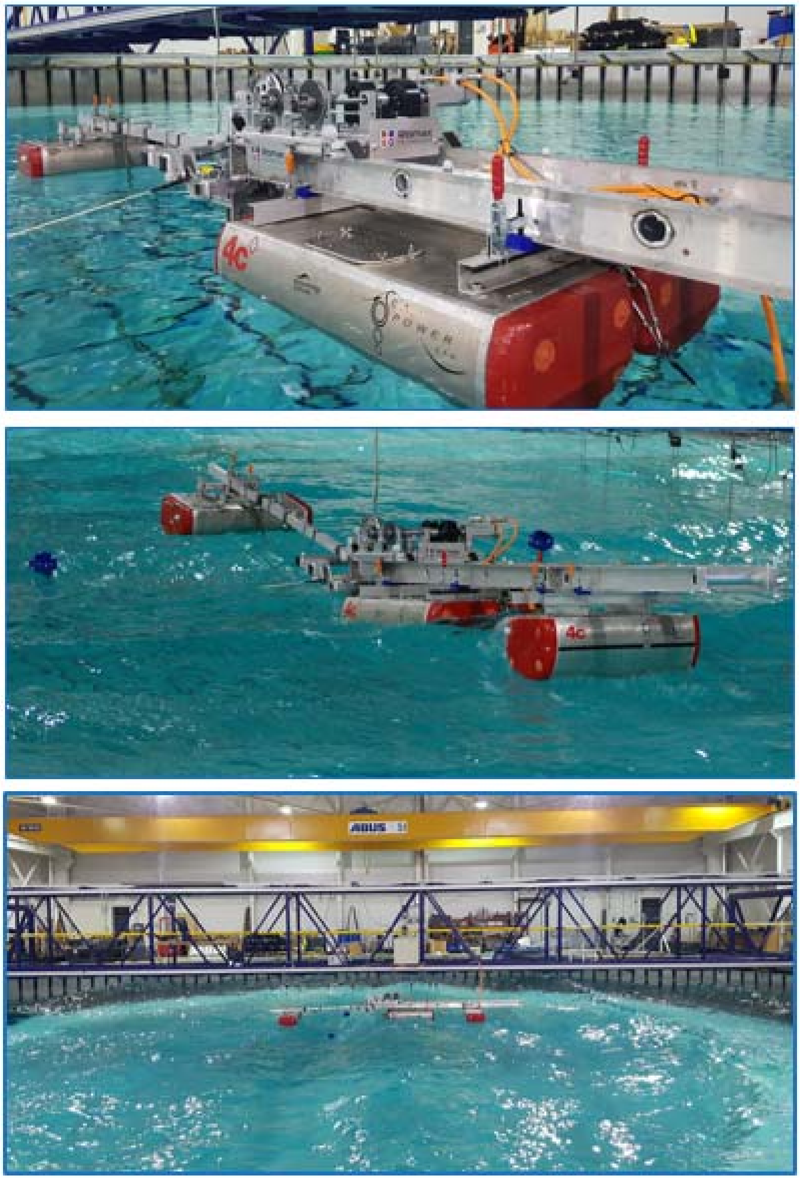

Figure 4: Tank Testing of SeaPower Platform with representative PTOs

This has allowed estimates of Annual Energy Production to be refined, and the behaviour of the PTO systems to be understood in the most realistic environment achievable at this scale.

Applicability to WEC Device Types

The PTO is expected to be compatible with any WEC type which produces relative motion between two bodies around a single rotation axis, as listed below in Table 2:

Table 2: Romax PTO's compatibility for each WEC device type

WEC Device Type	Compatibility
Attenuator	*Any attenuator type WEC where the relative motion between two bodies is rotation around a single axis - as has already been demonstrated with the SeaPower platform.*
Point Absorber	*Any point absorber WEC through conversion of linear to rotary motion through a cable drum or similar solution.*
Submerged Pressure Differential	*Any submerged pressure differential WEC through conversion of linear to rotary motion through a cable drum or similar solution.*
Oscillating Wave Surge	*Any oscillating wave surge converter type WEC where the motion between flap and base is rotation around a single axis. The PTO is well sealed and readily adapted to submerged operation.*
Rotating Mass	*Any rotating mass type WEC where the ability to perform indefinite complete rotations is a distinct advantage.*

The project has demonstrated the feasibility of providing an extremely large torque reaction capacity (up to 40MNm) to the SeaPower platform, which is a large (100m length at full scale) attenuator class device. However, the technology may readily be scaled down to suit even the smallest WEC devices while retaining the principle advantages of high efficiency and established, cost-competitive supply chains.

Oscillating water column, overtopping, and bulge wave devices are not considered to be target platforms for this PTO technology.

Summary of Performance against Target Outcome Metrics

Metric	Target Outcome	Actual Outcome
Affordability	The Stage 2 project will primarily investigate the potential of alternative gearbox layouts to enhance energy production. These layouts add additional components compared to the baseline layout considered during Stage 1, and there is expected to be a resulting slight increase in CapEx. A key output of Stage 2 will be to quantify this increase and demonstrate whether or not it is outweighed by the increased quantity (and quality) of energy capture. Demonstrate the potential of alternative gearbox configurations to reduce inertial loading, enhance controllability, and decouple parts of the mechanical system from the WEC input.	The Stage 2 project demonstrated that a mechanically rectifying gearbox using one-way clutches is not a viable solution. In addition to increased CapEx with additional components, this gearbox is likely to experience very high transient and inertial loading, likely to lead to premature component failure and increased OpEx costs. A variable-ratio gearbox using a differential and two generators was shown to have the potential to achieve a small increase in AEP relative to a fixed-ratio gearbox, assuming both systems are using largely off-the-shelf power conversion solutions common in wind energy. However, this gain is of the order of a few percent, and does not appear to justify the additional CapEx associated with an additional gear stage and generator. At this stage, it appears that the most effective route to achieving a commercially viable PTO solution will be the baseline gearbox layout with a bespoke power conversion and smoothing solution on the electrical, rather than the mechanical side of the system. This will be the focus of the Stage 3 project.
Performance	The Stage 2 project will specifically explore variations on the baseline gearbox configuration, with the aim of extending the range of WEC speeds at which energy can be captured and converted to grid-compliant electricity. The aim will be to quantify any increase in AEP from these configurations, and to assess if this is sufficient to outweigh any additional CapEx associated with the additional components required.	Tank testing allowed the AEP to be predicted with increased confidence for a number of potential installation sites. The predicted AEP is lower than the values determined from simulation during the Stage 1 project, confirming concerns about the simulation model behaviour. However, they are still sufficient to produce an LCoE figure which approaches WES' long-term targets.

	Tank testing of the combined PTO and WEC will be carried out, both for the baseline PTO and the best alternative configuration found during rig testing. This will allow validation of previous AEP values determined from hydrodynamic simulation.	It was not possible to demonstrate a significant increase in AEP from the alternative gearbox configurations for the SeaPower Platform
Availability	The Stage 2 project will not directly address availability, although some of the layouts under consideration may provide benefits in improved load-shedding and reduction in inertial torque, so reducing failure rates. Although the primary reason for considering the alternative configurations at Stage 2 is to enhance the energy capture in normal operation, these layouts also have potential for protecting the mechanical systems from failure and, where component failure is imminent, prolonging life until a suitable weather window for replacement.	The differential layout has the potential, if combined with a suitable remote condition monitoring system, to allow certain parts of the system to be protected from high loads. However, the benefit of this cannot be determined with sufficient certainty to justify the increased cost and complexity of this solution.
Survivability	The Stage 2 project will validate the potential of alternative gearbox layouts to reduce the inertial torques experienced under extreme conditions.	The differential layout was demonstrated to be able to achieve the expected passive reduction of inertial torque in survival conditions.

Communications and Publicity Activity

Publicity		Information
Poster	Romax Wave Energy Transmission Module	Presented at: • WES Annual Conference, Edinburgh, December 2016 • Structural Materials and Manufacturing Processes Inception (SMMP) Workshop, Glasgow, April 2017
Press Release	Wave Energy Scotland	http://www.waveenergyscotland.co.uk/news-events/wave-energy-technology-projects-awarded-2m/
News Coverage	Tidal Energy Today	https://tidalenergytoday.com/2016/09/23/wes-bolsters-wave-energy-projects-with-2-million/
	REnews	http://renews.biz/104273/scots-splash-2m-wave-cash/

Recommendations for Further Work

In light of the findings of this project, the following decisions have been made regarding the choice of mechanical system:

- Focusing on the baseline configuration offers the most efficient route to achieving a first commercial deployment of the technology through the ongoing WES PTO programme.
- While the potential advantages of the differential configuration cannot be shown to outweigh the costs in the current context of the SeaPower platform, this balance may shift in other WEC applications. The knowledge acquired here regarding the performance of this system will be retained, and the possibility of further development considered as Romax Technology Ltd seek to increase their engagement with other WEC developers.

Among the key aims of this next stage of development are:

- Assessment of different options for power conversion, storage and conditioning systems, looking beyond the standard wind sector systems assumed thus far and assessing full-system LCoE in conjunction with WEC developers.
- The detailed design, manufacture and test of a bespoke generator optimised for a wave energy torque/speed distribution, building on the optimisation and concept design which has been carried out during the Stage 1 and 2 projects.
- Detailed design, manufacture and test of the power conversion system in conjunction with the gearbox and generator.
- Demonstrating the capability to carry out full-system modal analysis on the WEC/PTO system, and make appropriate modifications to minimise structural interactions with the control system.
- Achieve a significant increase in the development level of the control system.

Useful References and Additional Data

Document Number	**Description**	**Confidentiality**
UK-000496-DC-003-B	*Milestone 01a – identification of candidate layouts and concept design at 'full scale'.*	**Confidential**
UK-000496-DC-010-B	*Milestone 01b – design of small scale representations of candidate layouts.*	**Confidential**
UK-000496-DC-015-B	*Milestone 02a – design and procurement of test rig*	**Confidential**
UK-000496-DC-028-B	*Milestone 02b – assembly and commissioning of test rig*	**Confidential**
UK-000496-DC-042-A	*Milestone 03 – rig testing of PTO candidate layouts.*	**Confidential**
UK-000496-DC-045-A	*Final Confidential Technical Report*	**Confidential**
UK-000496-DC-002-B	*WES Annual Conference 2016 Poster*	**Non-Confidential**
UK-000368-DC-032-A	*WES PTO Stage 1 Non-Confidential Report: Wave Energy Transmission Module*	**Non-Confidential**