Quantor hybrid hydraulic PTO

WES PTO Stage 3

Public Report

Artemis Intelligent Power Ltd

This project has been supported by Wave Energy Scotland

1. Project Introduction

This project was a collaboration between Artemis Intelligent Power Ltd and Quoceant Ltd to develop a new form of hydraulic power transmission ideally suited to wave energy, called 'Quantor'. This stage 3 project followed a stage 2 project to develop the Quantor concept and practically demonstrate the capability of Digital Displacement Pump Motors (DDPMs) to enable it. Quantor provides continuously controlled torque or force with the efficiency and power capacity of a quantised system.

In this stage 3 project, a full Quantor Power Take Off (PTO) system was developed and demonstrated, using a specialised test rig to emulate the wave excitation and dynamics of a Wave Energy Converter (WEC). Tests of a real system allowed the control algorithms and hydraulic hardware to be refined and for detailed numerical models to be validated. The performance of larger systems was also projected using validated models, and designs developed and costed for integration into a variety of WEC types.

Amongst the most important aims for the project were:

- a direct demonstration of a full Quantor PTO working in realistic dynamic conditions;
- development and refinement of the necessary control algorithms and hydraulics hardware to enable this;
- quantified performance in terms of efficiency across the power range, and the accuracy and smoothness of the controlled torque;
- detailed and accurate numerical models validated by physical tests, and ability to project performance for larger and different arrangements of Quantor;
- Costed Front End Engineering Designs suitable for a range of WEC applications;
- the development of the underlying DD technologies to enable implementation of the Quantor PTO into the megawatt range.

The project was successful in these meeting these aims.

2. Description of Project Technology

Quantor is based on the PTO system that was proven in the Pelamis wave energy converter. By switching in and out different combinations of the primary actuators (hydraulic cylinders in that case), power could flow direct to and from the energy storage with practically no losses. This system was able to absorb over the very wide range of input power required in real seas, whilst outputting a smoothed average to the grid with measured average efficiency of around 60-70% even at part load. This system delivered hundreds of MWh to the grid and was iteratively improved over many years against reliability, performance, and cost targets, so was considered the state of the art from which to improve.

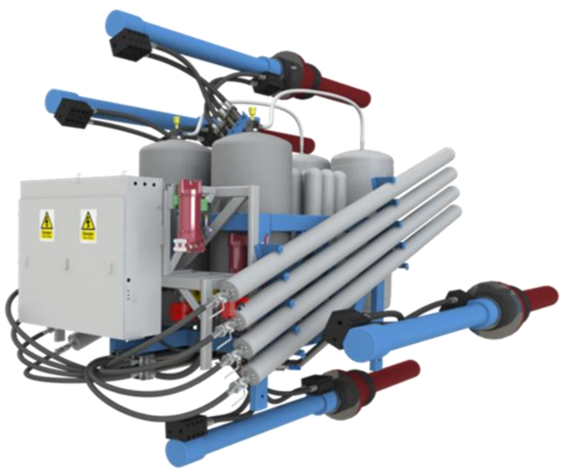

Figure 1: The Pelamis PTO system (WEC structure removed) with multiple hydraulic cylinders which are pressurised or depressurised in sequence to control the load. This quantised primary transmission and the iteratively proven and improved secondary systems of energy storage and hydraulics and electrical integration are inherited by Quantor.

Figure 2: Cross section of the DDPM pump motor used to provide continuous pressure control and smooth power output in the Quantor system.

However, a major downside of this previous approach is that the resulting load in discrete steps, which is not ideal for absorption control or even feasible for driving winch lines or for low inertia WECs. Also, hydraulic cylinders have end-stops, which presents a serious design conflict in wave energy.

With Quantor PTO, a new state of the art was sought by introducing continuous load control, and rotary response capability, while otherwise retaining the proven benefits of the quantised approach. The Quantor concept is that most of the demand force or torque can still be delivered by switching the pressure on or off in multiple actuators, but that the gap left between that quantised load and the smooth, ideal, demand load can be filled in with a new element. This is illustrated in Figure 3.

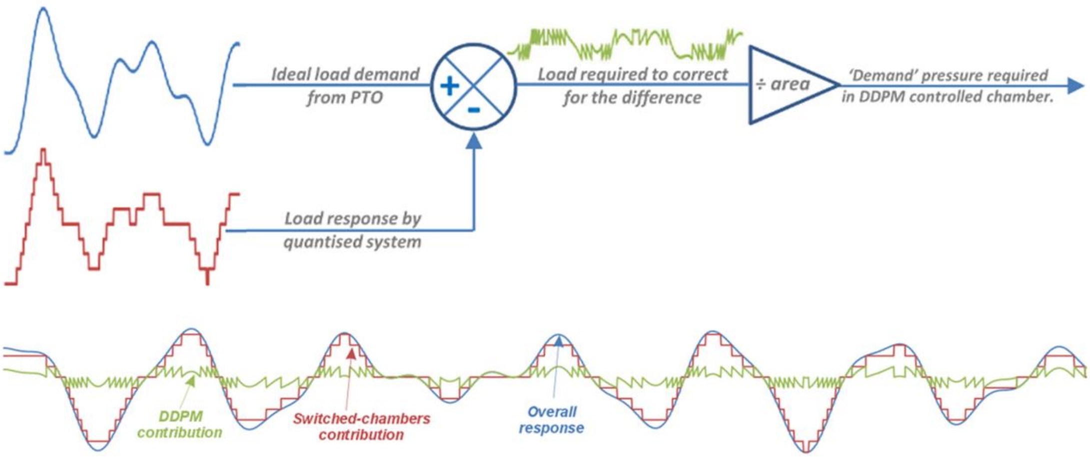

Figure 3: Operating principle of Quantor. The Quantised load is supplemented by a rapidly varying and error correction system to provide a smooth net output.

Digital Displacement Pump Motor systems, developed by Artemis Intelligent power, have the capability to control pressure very quickly under oscillating flows, whilst also efficiently transmitting power. As shown in schematic form in Figure 4, multiple hydraulic motors are switched by fast acting valves to give the quantised load and efficient bulk power transmission, but one or more of these motors is tightly pressure controlled by a DDPM to give a smooth output load in total for the WEC. A second DDPM on the same shaft exchanges the power with the storage system and counters the transient loads to deliver smoothed output torque to the electric generator. The number of motors can be increased to give much greater torque and power range from the same DDPMs but with similar fixed losses. In this arrangement, most of the power is handled efficiently by the big steps in load, while some power is channelled through the continuously variable DDPM system. The DDPM and its fixed losses (still much lower than conventional pump motors) can be sized to handle only a fraction of the rated power whilst providing smoothing for the entire load range across all powers.

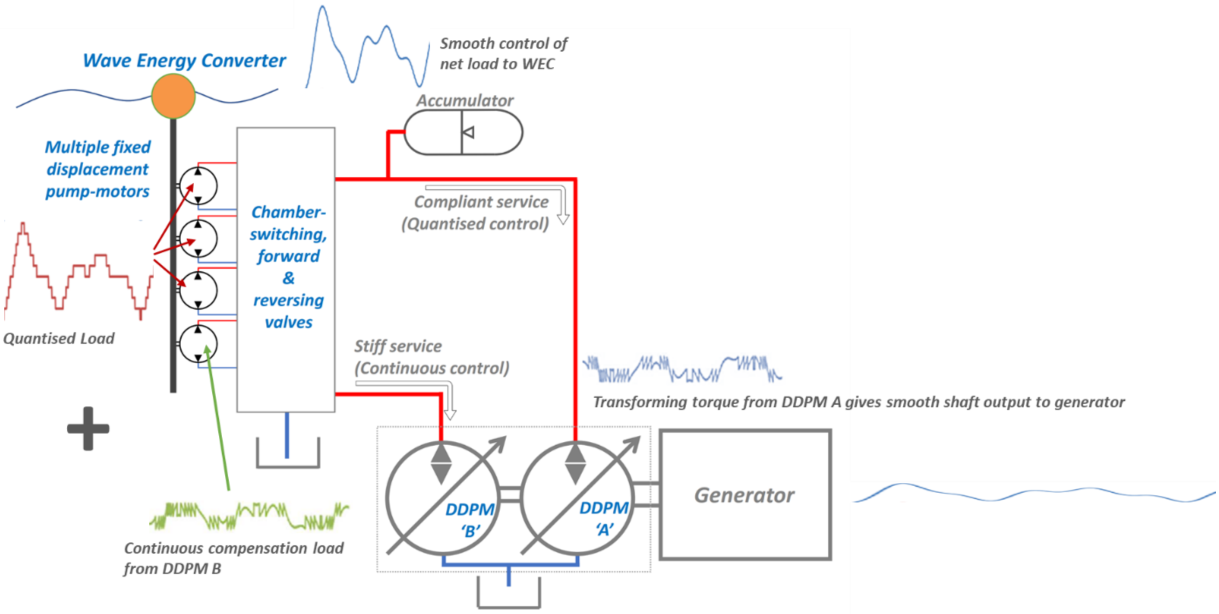

Figure 4: High-level schematic of Quantor PTO system.

The rotary actuators may be arranged around a central ring gear to provide the required balance of speed and load rating. For a linear or short-stroke/high-force PTO, hydraulic cylinders may be used, or the rotary actuators may be arranged on a rack and pinion to give a longer stroke and higher volumetric efficiency than would be possible for a hydraulic cylinder. Both the primary actuators and DDPMs may be sized according to the load and power rating required. The system is highly modular, with the load ranged also scalable simply with the number of primary actuators.

The main benefits Quantor is intended to deliver are:

- Continuous torque or force control with reactive power capability for generalised WEC control
- Smooth power output at high efficiency from irregular instantaneous power absorption
- General applicability to a wide range of WEC types and ratings, with very high load ratings possible
- Cost effective and reliable, especially for utility scale power

The previous stage 2 project demonstrated the DDPMs ability to deliver the rapid pressure control required for Quantor to work, while delivering smooth electrical output to the grid. In stage 3 the scope was widened to build and test a fully integrated Quantor PTO – directly demonstrating all functionality and allowing measurement of performance.

3. Scope of Work

The project consisted of 5 main work streams, with closely linked activities, inputs, and outcomes. Each of these contributed toward the overall objective of creating a Quantor PTO that works reliably, and that can provide the required performance and cost for a range of WEC types, powers, and load ratings.

3.1. Market and applications

In parallel to the core technology development and demonstration programme, Quoceant produced draft designs for integrating Quantor into a range of WECs, using different actuation mechanisms and with average power ratings from 100kW to multi-MW. Quantor was also adapted to direct rotary drive, rack-and-pinion, and cylinders.

Detailed costs were derived for a wide range of Quantor families offering smooth output power ratings from <100kW to 3MW (corresponding to peak inputs of 20MW), and torques from 100kNm to 20MNm. These costs included all systems required to integrate the PTO as either a direct rotary or winch drive, including energy storage and generation, and bearing and structural integration. These direct cost for different design were then used to derive generalised cost metrics in terms of £ per kW smooth electrical output rating, and £ per kNm of peak torque rating, showing trends and allowing preliminary specification matching with WEC developers. In addition to initial cost estimates, projections were made to volume manufacturing costs using conservative learning rates. The reliability aspects of new Quantor features were also discussed in the context of existing applications of components.

Simulation models were applied at every stage of the project and grew in sophistication to support the detailed design work as the design progressed. A full system simulation was thoroughly validated at both the component level and for the system as a whole. Validating at the component level allowed the model to be confidently extrapolated with additional and alternative, independently validated, motor models. The simulations were generalised and streamlined for fast computation, allowing robust PTO efficiency projections to be produced for a wide range of Quantor scales and powers (efficiency of the PTO is the average output electrical power divided by the average mechanically absorbed power input to the PTO).

3.2. PTO system test-rig

To develop Quantor technology, demonstrate its operation, analyse its performance, and validate numerical models, it was necessary to build not just the PTO system itself but also a test rig to drive it under repeatable and realistic dynamic conditions.

The chosen architecture for the test rig was selected from a range of preliminary concepts using simulations and preliminary design exercises. This was followed through to a detailed design in parallel with the Prototype Quantor PTO system. The test rig was fully specified, the components procured, assembled, and commissioned in preparation for fitting the PTO. Once the PTO was fitted and tested under prescribed motion, the hardware in the loop WEC emulation system was commissioned, using PTO load feedback to place the Quantor system in a virtual WEC

A 300kW rated electrical drive successfully emulated the wave forces, using measured feedback to derive the WEC response. The geared flywheel concept was successful, allowing a relatively small and affordable drive system to represent the wave excitation for a WEC in the 10s of kW mean power range, with an oscillating flywheel emulating WEC inertia physically. The PTO actuators operated in the same speed and power range as in the real WEC being emulated.

The test rig can emulate a variety of WECs, depending on the hydrodynamics model used in the drive control software. The physical flywheels may be interchanged to represent different WEC masses, and the drive can supplement this with virtual inertia to trim. While driving the PTO through prescribed motion is most useful for characterising detailed aspects of performance and efficiency, the virtual WEC approach is very useful for direct assessment of control strategies applied to the real PTO. This type of facility offers the closest thing to a real WEC and wave tank for PTO and control systems.

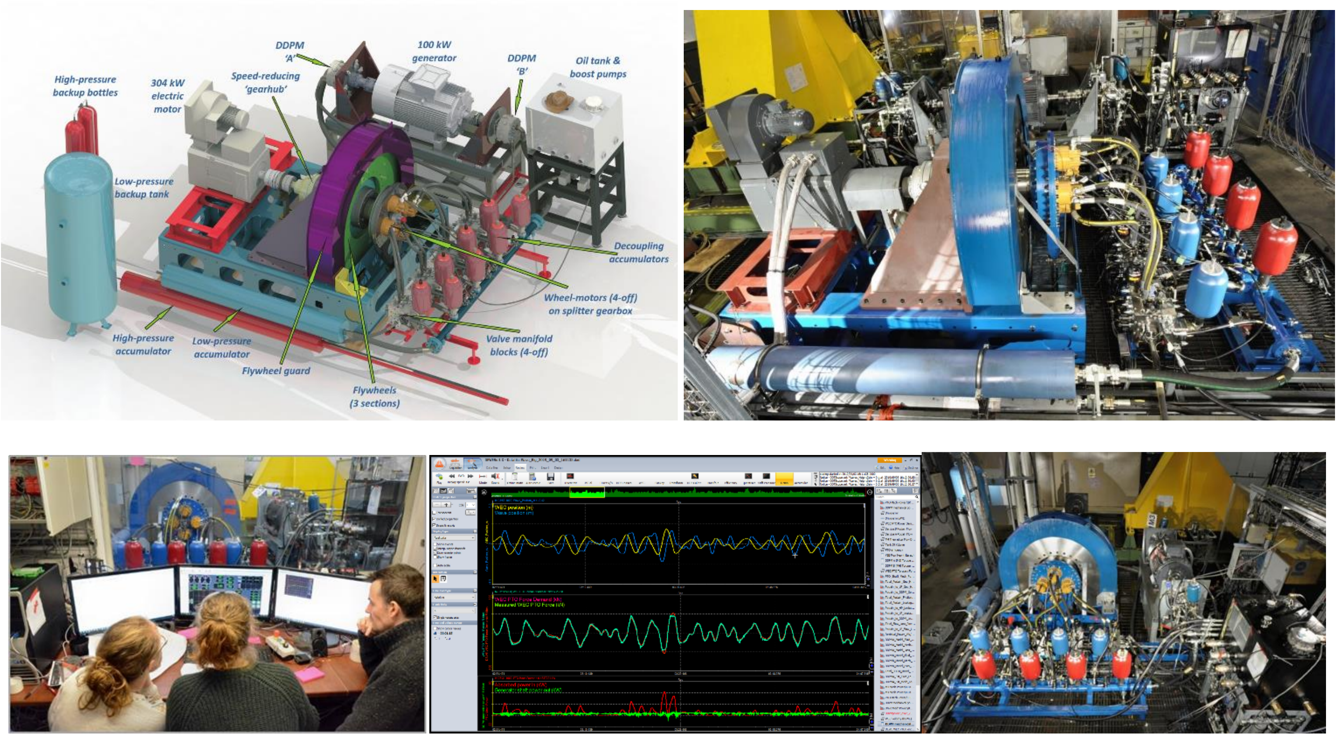

Figure 5: A 300kW rated electrical drive emulates the wave forces, using measured feedback to derive the WEC response. An oscillating flywheel emulates the WEC's inertia physically. The PTO actuators (yellow in the picture), are conventional fixed displacement wheel motors.

3.3. Quantor development

New control algorithms were developed from concept to real time implementation, to enable directional control of rotary actuators and allow switching between quantised and continuous pressure control on each. Detailed simulations of the hydraulic circuits were created and used to test the circuit designs with the real time control prior to prototyping. This simulation approach highlighted issues with both preliminary circuit designs and the need for control functionality, allowing both to be solved before real hardware testing where possible. The integrated hydraulic circuits central to Quantor were prototyped in stages to debug designs and component selection prior to procurement of the four prototype control blocks for the full PTO system. Preliminary control and hardware tests were conducted on a miniature test rig with a single motor, using a proportional valve in place of the DDPMs. Integrated control of the DDPMS was developed using simulations before the whole real time control was brought together with the Quantor PTO on the rig. The DDPMs were tested and characterised independently before integration with Quantor on the test rig.

Once fully assembled and commissioned on the test rig, the Quantor PTO was systematically tested through a wide range of conditions and control settings to characterise the performance. The efficiency and loss breakdown was measured in detail across a wide range of powers and control conditions, including reactive power and different combinations of quantised and continuously control services. This efficiency provided the basis for simulation model validation and excellent agreement was achieved throughout.

The project benefitted greatly from staged testing of hardware, allowing issues to be found and resolved earlier and with less effort than if the full rig was built in one go. The integrated hydraulic control circuit went through three iterations of prototype testing, with the controls and hardware evolving efficiently at each stage.

Simulation models were applied at every stage of the project and grew in sophistication to support the detailed design work as the design progressed. These simulations were later thoroughly validated and streamlined for FEED design work and performance projection.

New quantised control techniques were required to supplement the DDPM flow during load transitions whilst retaining smooth torque output. Signal processing methods were applied to rapidly tune the control system to the individual control valves based on a dedicated automatic test procedure, analogous to tuning an engine management system. This reduced residual ‘blips’ in torque to be negligible without requiring additional flow from the DDPM. The load control performance exceeded expectations in terms of smoothness and responsiveness, with effective latency of well under 10ms in load control making filtering of signal feedback noise the dominant source of closed loop phase lag. This technique can be applied to much larger systems, successfully decoupling the DDPM capacity specification from the transient flow requirements. Quantor was demonstrated successfully with performance meeting or exceeding expectations at the start of the project. For the first time quantised and continuously controlled elements were integrated on a common set of primary actuators to provide continuous and highly-responsive control of the PTO loads while maintaining smooth power output at high efficiency.

3.4. 100kW DDPM core Technology

During the Quantor programme there was a significant focus on the development of a 96 cc/rev Digital Displacement pump/motor. This machine was a development of the pre-existing Artemis C8 pump/motor of the same size. While the C8 series of machines were complex to build and only ever envisioned as prototypes, the M-96 DDPM machine was developed with a view to it being manufactured at a reasonable cost, with consistent performance and good durability. The separate LP and HP valves of the C8 were replaced with a single coaxial valve unit with annular valves, both of which were actuated by a single coil.

Lifetime testing was conducted of the core cycling components of the DDPMs at both 100kW and MW scale. The designs of these core components were refined the designs’ robustness and reliability proved in accelerated cycle tests. Environmental tests were also conducted of the DDPM components new to the offshore environment. The machines which were installed in the Quantor test rig were the result of this rigorous process and worked flawlessly in the final tests. Their performance characteristics outstripped all previous machines in terms of idle loss, efficiency, effective cylinder displacement and top speed.

3.5. MW-scale DDPM technology

Development of the larger, 40cc cylinder, Digital Displacement pump/motor was included in the project to ensure that the power range of the Quantor system could be enlarged to work with PTOs that would be needed for grid-scale WECs. Artemis had demonstrated this size of machine in the previous stage 2 project.

The M-120 design that was conceived for the Quantor programme essentially took all of the best features which had been evolved at Artemis and incorporated them into a single machine. In the end this greatly resembled the M-96 machine, but with significant variations in proportions of various components due to the effects of scaling of fluid flow, stresses, etc.

The MW-scale machine, which was developed during this programme, started much further back than the M-96, but of course benefitted from the knowledge that was being gained on the similar but smaller machines. The programme started with a specification and a form-factor, then proceeded to a detail design and analysis of the components. The resulting components were made, assembled into a single cylinder test rig, and their performance confirmed and gradually improved. When the initial targets of performance and durability were met, a three-cylinder machine was designed to incorporate these components. A test rig was prepared and the machined parts acquired. After the machine was built and commissioned, performance and durability tests were conducted.

The programme was blessed with much early success, and after relatively few iterations completed a 680 hour test at elevated pressure. This machine shows great promise for the future and could be the basis of a production machine when the market pull justifies the remaining costs of a complete durability testing programme and the development for production.

4. Project Achievements

Quantor was demonstrated successfully with performance meeting expectations set at the start of the project, in terms of overall conversion efficiency and continuously variable control of torque. The test rig was constructed on budget and operated as expected, providing a new test platform for PTO testing including WEC dynamics. For the first time quantised and continuously controlled elements were integrated on a common set of primary actuators to provide continuous and highly-responsive control of the PTO loads while maintaining smooth power output at high efficiency.

The test rig was a conceptual challenge. Multiple options of drive were assessed, and iterations of the design were worked through in simulations before converging on an architecture for rotary PTO testing with safe end-stop free operation. The energy storage and reactive power capability of the Quantor PTO meant that the rig required a very robust set of safety interlocks to ensure that the PTO could not back drive the rig unloaded, and these were a challenge to integrate with the conventional drive system once the build was underway. However, these safety systems did successfully prevent any damage on multiple occasions when unexpected drive interruptions occurred during testing.

The project benefitted greatly from staged testing of hardware, allowing issues to be found and resolved earlier and with less effort than if the full rig was built in one go. In particular, the key Quantor integrated hydraulic control circuit went through three iterations of prototype testing, with the controls and hardware evolving efficiently at each stage. Without this approach to testing independently where possible before integration, the whole Quantor system would not have worked as well as it did without expensive overhaul.

Simulation models were applied at every stage of the project and grew in sophistication to support the detailed design work as the design progressed. A full system simulation was thoroughly validated at both the component level and for the system as a whole. Validating in detail at the component level allowed the model to be confidently extrapolated with additional and alternative components, including independently validated motor models. The simulations were generalised and streamlined for fast computation, allowing robust efficiency projections to be produced for a wide range of Quantor scales and powers. Figure 6 shows some simulation results plotted over real measurements.

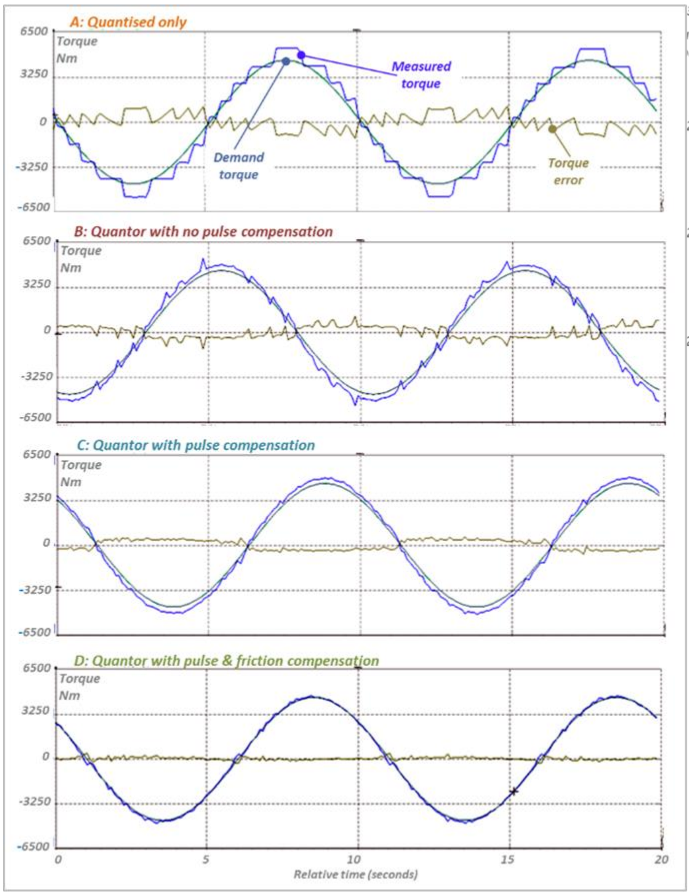

Figure 7: Measurements of the torque output from Quantor under prescribed regular wave motion. Control and hardware features are added to result in a smooth accurate output torque matching the demand.

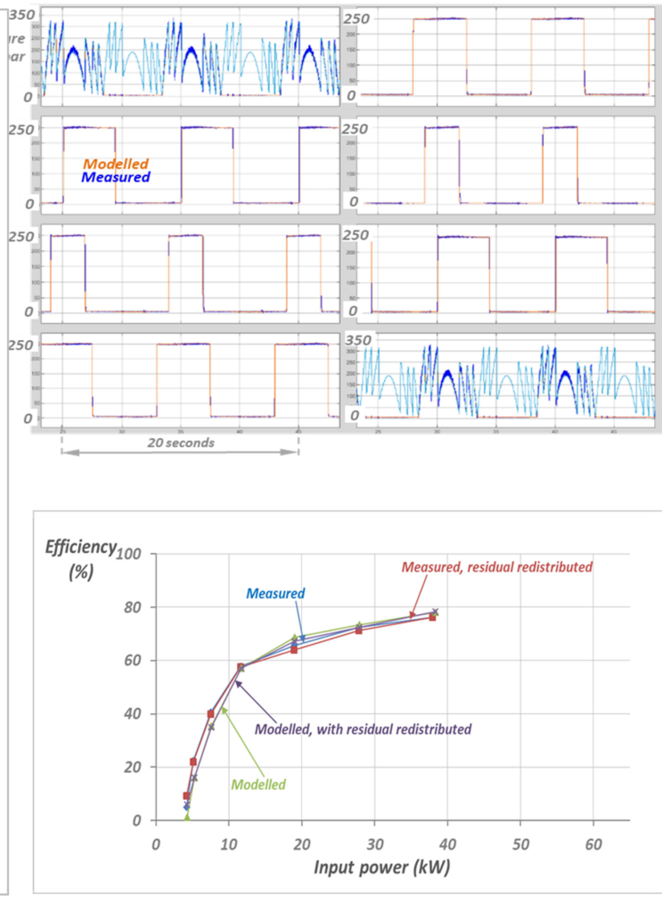

Figure 6: Comparisons of real measurements and simulation results when fed only the same motion input. (top) time series of port pressures showing the mix of quantised and continuously controlled motors. (bottom) average efficiency against average input power for the small rig system.

A key risk identified at the start of the project was the reliance on new quantised control techniques to supplement the DDPM flow during load transitions whilst retaining smooth torque output. This aspect did indeed prove very challenging, and so additional effort was required to develop new control and adjustment methods. Signal processing methods were applied to rapidly tune the control system to the individual control valves based on a dedicated automatic test procedure, analogous to tuning an engine management system. This reduced residual ‘blips’ in torque to be negligible without requiring additional flow from the DDPM. The load control performance exceeded expectations in terms of smoothness and responsiveness, with effective latency of <10ms in load control making the filtering of signal feedback noise the dominant source of closed loop phase lag. This technique can be applied to much larger systems, decoupling the DDPM specification from the transient flow requirements. Figure 7 shows measurements from Quantor under prescribed motion tests, showing the smooth torque control being delivered with the progressive addition of control and hardware features.

The efficiency was measured at over 70% for powers over 40% of rating, as the PTO delivers smooth electrical output. Simulations showed that larger systems benefit from higher efficiency due to relatively lower friction and fixed losses. In addition to directly measuring overall efficiency, the simulations were validated in terms of the loss breakdown throughout the system. This approach to detailed model comparisons provided great insight into where the real system was not initially operating properly as modelled, allowing issues on the hardware to be resolved and agreement reached. This detailed view of the power flows also suggests where the system may be improved further. Example Sankey diagrams are shown in Figure 8.

Figure 8: Sankey diagrams showing the detailed breakdown of average power flows and losses over time. The model was fed only the same input shaft motions, so we see the result of simulating all control and PTO hardware. Underneath are direct measurements from the test rig. The two agree in overall efficiency and in the breakdown across the power range.

Once validated, the simulation was extended to allow additional motors and for different independently validated motor models to be integrated into full system models. This modular approach allows for Quantor to specified for a very wide range of torques and power ratings – from under 100kW to 3MW or more. This whole range was the subject of a simulation study and costed design exercise, arriving at projected efficiency curves and costs for a family of Quantor solutions.

In parallel with this WES project, Quoceant has undertaken a number of commercial projects toward the integration of Quantor in different WEC types, using different actuation mechanisms and with average power ratings from 100kW to multi-MW. This has provided insight into the requirements for each type, including the line handling of winch systems, and the design of gear transmissions for long service life. Quantor was also adapted to direct rotary drive, rack-and-pinion, and cylinders. Artemis, also in parallel, directly developed and tested the larger DDPM sizes required for scale-up under Work package 6.

Specifications for a generalised and costed family of Quantor designs based on well validated models is a key outcome of the project. Detailed costs were derived for a wide range of Quantor families offering smooth output power ratings from <100kW to 3MW (corresponding to peak inputs of 20MW), and torques from 100kNm to 20MNm. These costs included all systems required to integrate the PTO as either a direct rotary or winch drive, including energy storage and generation, and bearing and structural integration. These direct cost for different designs were then used to derive generalised cost metrics in terms of £/kW, and £/kNm, showing trends and allowing preliminary specification matching with WEC developers. In addition to initial cost estimates, projections were made to volume manufacturing costs using conservative learning rates. The reliability aspects of new Quantor features were also assessed in the context of existing applications of components. For example, the new addition of wheel motors with a strong track record in demanding off road applications.

4.1. Summary outcomes

- A control system, design framework, and components for the new state of the art Quantor PTO system scalable and capable for the full range of WEC applications. Robust and fault tolerant and providing 4 quadrant continuous control with low fixed losses, as required for spectral power regime.
- Development and demonstration of a new PTO test rig concept to emulate different WEC hydrodynamics using a hardware in the loop drive system, combined with physical inertia to directly represent the WECs inertial properties under speed scaling, keeping the PTO motors in the correct speed and power regime.
- Development and demonstration of a whole Quantor PTO system operating under realistic dynamic and power conditions, albeit at small scale commensurate with the rig budget.
- Systematic testing and measurement of Quantor delivering continuously controllable torque output with acceptable levels of residual disturbance from the underlying quantised control, and at levels of efficiency expected. (Rig tests of the small-scale system directly showed average efficiency of well over 70% in regular waves, implying efficiency well over 70% for larger systems in rated irregular conditions.)
- Creation of a range of highly accurate simulation models validated against experiments across the power range. These tools allowed for design integration and performance projection of a wide range of systems, and for potential integration of Quantor models into wider WEC simulations.
- Addressing of the engineering requirements for integration of Quantor into different WEC types and create FEED designs for a range of WEC applications. These include direct rotary drives, winch drives, rack and pinion linear drives, and linear or rotary cylinder arrangements.
- Design specifications and cost & performance projections for a wide range of power, torque and speed ratings, expressed in terms of £/kW and £/MNm for both initial systems and volume manufacturing. For example, a volume manufacturing cost reducing to <800£/kW rating for fully featured and structurally integrated Quantor PTO in the MW range.
- Advances in core DDPM technology to enable and prove robust and efficient operation at both the 100kW and 1MW power ranges, as required to enable Quantor application in the field.

5. Applicability to WEC Device Types

From the outset, Quantor has been developed as a general PTO solution for the majority of WEC types. The modular core hydraulic transmission is adaptable to a wide range of actuator sizes, and to either rotary actuators (i.e. pump/motors) or hydraulic cylinders. Quantor is scalable from tens of kilowatts up into the megawatt range. A comprehensive set of design specifications were formed for 3 families of rotary PTO, either direct or as a winch.

Rotary actuators may be arranged to provide direct PTO at a hinge, via a line on a winch drum, or in a rack-and -pinion arrangement for long stroke linear PTO. Hydraulic cylinders may be arranged in-line or about a single or multi degree of freedom hinge mechanism. These different architectures allow for application of Quantor to restricted motion high force applications such as hinged barges or surging flaps, or to long motion lower force WEC types such as heaving buoys. Design have also been advanced for piston arrangements suitable for OWC or bulge wave PTO.

The greatest benefits from Quantor are expected to be from WECs with the potential to increase power absorption through generalised continuous control, making use of the reactive power capability to maximise absorption. The high efficiency of any PTO, even at part load, is crucial to economic performance – and this must be the case in realistic irregular waves when the average absorption is a small fraction of the peaks.

Quantor PTO is well-suited to multiple degree of freedom WECs as multiple actuators can share the same energy storage and secondary conversion equipment. Such sharing of components offers benefits in capital cost, efficiency, reliability, and utilisation. For example, shared energy storage allows for local smoothing between degrees of freedom as well as overtime, increasing the smoothing capacity of a given storage volume.

Quantor also has the potential for wide application in non-wave energy markets where high bandwidth and accurate control of force is required over a wide power range. Outside renewable PTO systems, heave compensation systems with high reactive and peak power requirements and are increasingly common on offshore cranes and winches. Conventional systems are inherently very inefficient and expensive compared with a potential Quantor approach.

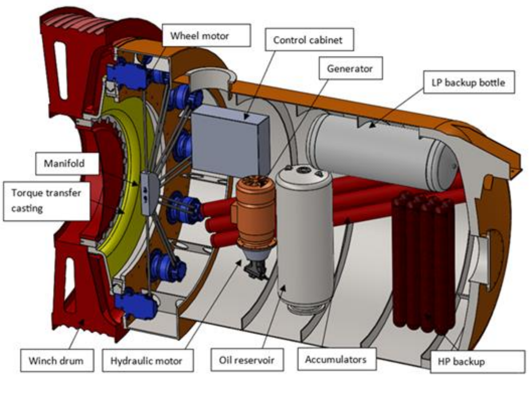

Figure 9: Quantor PTO driving a winch drum. Radially or tangentially connected motors drive a central ring gear, with a shared slew ring bearing. All secondary conversion equipment is in a modular package. A similar arrangement can be applied to a hinged WEC.

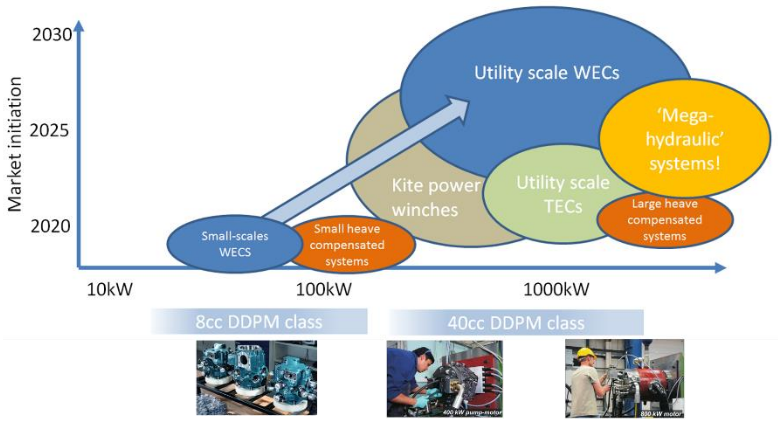

Figure 10: Markets for Quantor with increasing scale and power rating.

6. Summary of Performance against Target Outcome Metrics

Quantor performance was demonstrated and quantified across a wide range of conditions and control settings. The affordability was assessed across a wide range of different Quantor families, with cost metrics established relating power rating, load rating, and speed limitations to the total integrated system cost, backed by purchasing experience. Availability and survivability were addressed through accelerated cycle testing of core components and the demonstration of fault handling mechanisms on the rig. The hydraulic circuit can be split to provide redundancy and individual motor and valve faults may be disengaged with minimal impact the overall system availability.

In other contexts, the two distinct technologies within Quantor (quantised chamber-switching and Digital Displacement®) have undergone extensive reliability testing, including accelerated cycle testing and, for the quantised components, operational testing over thousands of hours in the Pelamis WEC. For this project the new DDPM technologies underwent extensive accelerated cycle testing with iterative design improvement to demonstrate reliability and robustness for the application. The Quantor system under test suffered no failures in service except for one valve station, which was handled without interrupting operations and without any measurable degradation in performance.

Survivability is enhanced by the inherent failsafe capability of hydraulics, which can maintain restraint or default to a 'hold-down position' in the absence of electrical and control systems. Simple mechanically driven controls can also be arranged as a fallback for any centring or tension holding requirements.

The efficiency of Quantor was measured directly for the small system installed on the test rig, achieving conversion efficiency of >70% over the upper half of power range. This met expectations, although motor friction was somewhat higher than was anticipated at the start of the project, the simulation models agreed extremely well once informed by supplier engagement and testing. The simulations of larger systems than could be tested directly on the rig show that efficiency improves with scale as expected, with both friction and fixed losses relatively lower compared with output. Figure 11 shows the projected characteristic regular wave efficiency against mean input power for a range of Quantor power ratings. The small system tested on the rig is at the far left (2x255cc). Figure 11 shows an illustrative projection of efficiency in irregular waves based on these results.

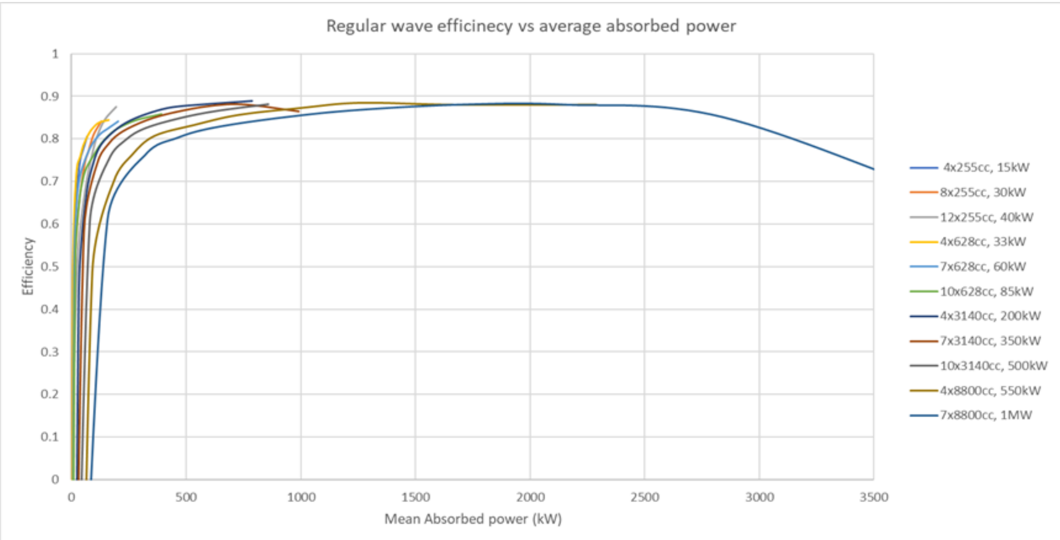

Figure 11: Characteristic mean efficiency vs mean power in regular wave for a wide-ranging family of Quantor systems

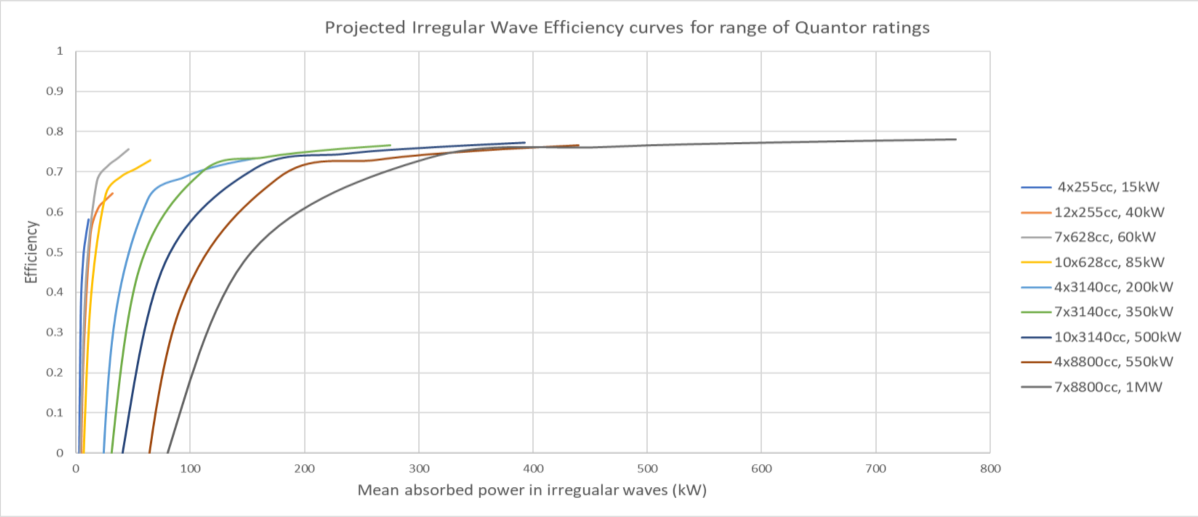

Figure 12: Illustrative projection of efficiency in irregular waves with respect to the mean power input, for same family of Quantor PTOs as in Figure 11. Actual performance would depend somewhat on the specific control used and the type of WEC response.

Most Quantor components are either in volume manufacture already or, in the case of the DDPMs, in the process of entering volume manufacturing for existing markets. Major cost reductions are still available from volume procurement and assembly, but the greatest challenge to commercialisation within wave energy remains in bespoke WEC integration and the wider economics of the wave energy platform – the next stage of the journey.

A cost per kW metric of 800-900£/kW was targeted at the start of the project. The Quantor designs including bearings and structural integration gave projected costs falling to <900£/kW for volume manufacture machines over 800kW rating. Smaller machine are disproportionately more expensive per rating due to the higher influence of fixed costs. Costs of early machines are inevitably also much higher than is possible in the longer term. Costs were related to both the load and speed specifications of the system with reference to a wide-ranging set of tabulated designs.

7. Communications and Publicity Activity

This project was presented to the WES annual conference along with poster displays in 2017, 2018, and on completion in 2019.

A paper was presented during the project to EWTEC 2019 describing Quantor and the process of testing and model validation, including detailed breakdown of losses: [Sarah Acheson, Ross Henderson and Daniil Dumnov, 2019, Simulation of Digital Displacement Hydraulic Power Take-Off for Wave Energy Converters; Proc. EWTEC Conference.]

Artemis have produced leaflets publicising the project and Artemis and Quoceant have presented these at commercial conferences around the world as part of general business development activity.

Several magazines and online news outlets reported on the project in response to press releases supported by Quoceant and Artemis, including an interview-based story in the maritime journal.

8. Recommendations for Further Work

The next stage of the technology development is associated with moving out of the lab into real applications. Therefore, the targeting of further activity towards practical application is somewhat specific to the nature of the application and the associated integration issues that arise. For example, the application of winch drum PTO systems requires research and development into line handling and control issues. However, many common elements could be developed further within a core R&D framework.

The Quantor system demonstrated in the lab during this project was at the very lowest end of the power range, to suit the electric drive system and budget of the test rig. While sufficient to both prove all the technology elements and validate the simulations, there remains a number of practical integration issues to resolve for larger systems prior to any potential deployment in a real WEC. Perhaps chief among these is the detailed design of the motor ring gear system at large scale, allowing for structural deflection without inducing excess wear. Further work could usefully focus on this aspect. A dedicated gear test rig could use a pair of counteracting motors to test these mechanical integration aspects independently of the power transmission, assessing sensitivity to structural stiffness and alignment. This may be combined with practical testing and demonstration of other aspects of integrated design such as inter-motor connections, shaft sealing systems, etc, and include long term wear testing of all components.

To prepare for higher power systems, the larger motors identified in this project could be tested individually to directly further verify their respective models in the Quantor regime, and to test the larger control valves required to carry the bulk power flow in the largest systems.

The core Quantor power transmission could be further advanced toward application with attention to automated fault detection and handling. The capability is already inherent and partially demonstrated but the associated front-end interfaces for real offshore application require substantial work to ensure robustness in the field.

The cut-in and low power efficiency could be substantially improved with the inclusion of base-load system in parallel with the main PTO. This technique was applied in Pelamis to deliver 60% efficiency down to below 10% of rating, but this would require novel integration of additional DDPM systems and freewheeling motor modes for Quantor.

9. Useful References and Additional Data

Websites:

- Artemis: www.artemisip.com
- Quoceant: www.quoceant.com

Background info (subject to copyright and/or registered access):

- WES Stage 2 public report: Hybrid Digital Displacement® hydraulic PTO for wave energy
- WES Knowledge capture reports: Pelamis Wave Power, Power Take-off Report.
- Salter S. H., Taylor, J. R. M. & Caldwell, N. J. 2002, Power conversion mechanisms for wave energy. Proc. Inst. Mech. Eng. M, J. Eng. Maritime Environ.216, 1–27.

- Henderson R., Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter, Renewable energy, vol. 31, pp271-283, 2006.
- Taylor J., Section 6.3.1., ‘Hydraulic energy conversion’ in: Ocean Wave Energy, Current Status and Future Perspectives, Cruz J. editor, Springer, 2007, ISBN 3540748954
- R. Yemm, D. Pizer, C. Retzler, and R. Henderson, “Pelamis: experience from concept to connection,” Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 370, pp. 365–380, 2012.

10. Publicity Material

[Please supply WES with any logos, images and video files that are non-confidential and available for WES to use to promote WES supported projects. Use the table below to provide filenames and descriptions for all such material. Files should be uploaded to the same milestone folder as the public report.]

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