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Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter

Ross Henderson *

Ocean Power Delivery Ltd, Edinburgh, Scotland, UK

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Abstract

The economic viability of a wave energy converter depends largely on its power take-off system. Active control of the power take-off is necessary to maximise power capture across a range of sea-states and can also improve survivability. The high force, low speed regime of wave energy conversion makes it a suitable application for high-pressure hydraulics.

This paper describes the hydraulic power take-off system employed in the Pelamis wave energy converter. The process of the system's development is presented, including simulation and laboratory tests at 1/7th and fullscale. Results of efficiency measurements are also presented.

Keywords: Hydraulic power take-off; Wave energy converter; Pelamis

1. Introduction

The extraction, by any wave energy converter (WEC), of useful energy from ocean waves requires that the waves apply force to some form of responsive mechanism able to resist the working force that the waves apply, and some form of reference against which that mechanism can react. The mechanism by which energy is transferred between the waves and the WEC, and subsequently or directly into useful form, is generally known as the power take-off (PTO). Control of the response of a WEC can be achieved through active control of the PTO.

Control of the PTO is central to the economic viability of wave energy; a major sustainable resource that has, as yet, remained untapped. It is important to show the potential of wave energy at an early stage by firstly, ensuring that machines can survive under arduous conditions, and

* Tel.: +44 131 553 9495.
E-mail address: ross@oceanpd.com

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secondly, by absorbing and converting a respectable amount of energy. These goals can, in large part, be achieved through control of the PTO.

To extract a maximum amount of power from the incident waves, the PTO should be capable of applying a restraining force varying appropriately with time as the WEC responds. This requires real-time measurement of response, and control of the PTO over the wave cycle. Moreover, to operate effectively across different sea-states, the control and PTO must be able to adapt such that power absorption is maximised in small seas and the risk of damage is minimised in large seas.

For maximum power absorption, a WEC should respond in resonance with the waves such that the exciting force and the response velocity are in phase [1]. While, with appropriate design, a WEC can possess inherent dynamics such that its natural response frequency is in the correct range to match the central excitation frequency of most sea-states, active control is necessary to maximise power capture across a range of sea-states and in irregular (realistic) seas where a range of component frequencies are present. Control can also play a vital role in improving survival characteristics although, whilst crucially important, this aspect is not generally expanded on in the existing literature.

2. Hydraulic PTO

Wave energy conversion can be considered a very suitable application for hydraulics. Waves apply large forces at slow speeds and hydraulic systems are suited to absorbing energy under this regime. Moreover, it is a simple matter to achieve short-term energy storage, necessary to achieve the smooth electricity production required for a marketable machine, with the use of cheap and available high-pressure gas accumulators.

Hydraulic systems have many favourable characteristics and many WEC proposals have incorporated hydraulic PTO in their design [2–4]. However, the majority of literature on PTO has focused on air turbines operating within oscillating water columns, such as employed in existing shoreline plants [5,6]. This is perhaps the result of researchers gravitation to the technology most deployed and recognised, rather than the ultimate suitability of air turbines as a means of wave power conversion.

Salter et al. [7] and Artemis Intelligent Power Ltd [8] have developed a novel digital hydraulic pump/motor, originally intended for a wave energy application, capable of offering a continuously variable transmission of hydraulic power at much higher efficiencies than conventional hydrostatic transmissions. While the technology is nearing commercial application, it is still at the prototype stage and unsuitable for immediate deployment in a WEC.

Eidsmoen [9] described a hydraulic control system using a latching strategy, originally suggested by Budal [10] and independently by French [11] to avoid the need for variable transmission or reactive power.

3. Pelamis PTO

The Pelamis [12,13] is an offshore, floating, slack-moored wave energy converter consisting of a set of semi-submerged cylinders linked by hinged joints. Ocean waves perform work on the Pelamis by moving adjacent cylindrical sections relative to each other across two degree of freedom joints. The two axes that comprise each joint are inclined to the horizontal to allow a net inclined response to be induced by the PTO, which resists and reacts against the relative angular motion of the joints. The inclined response offers an effective hydrostatic stiffness reduced from a vertical response, resulting in a natural frequency dependent on the slope. Thus, the machine can be designed with a resonant response matched to the dominant frequency of the wave climate in which it is to be installed, minimising the reactive power requirements of the PTO. The level of excitation transmitted to the resonant response can be controlled via the PTO.

The Pelamis PTO consists of sets of hydraulic cylinders that pump fluid, via control manifolds, into high-pressure accumulators for short-term energy storage. Hydraulic motors use the smooth supply of high-pressure fluid from the accumulators to drive grid-connected electric generators.

The Pelamis PTO can be examined and developed in two separate parts, which we will call the primary and secondary transmission. The primary transmission, consisting of the hydraulic cylinders and their controls, converts the work done by the waves on the structure to stored energy. The secondary transmission, consisting of hydraulic motors coupled to electric generators, converts the energy stored in the hydraulic accumulators into electricity transmitted to shore. This separation, provided by the high-pressure accumulators, allows efficient absorption over a large range of incident power.

The impeding joint moment provided by the cylinders must be varied throughout each wave cycle such that the waves do the maximum amount of work on the machine as a whole. Real-time control of the joint moment is achieved with the use of sets of electronically controlled valves, which control the flow of fluid between the hydraulic cylinders and the accumulator and reservoir. The valves are controlled to enable different combinations of chambers to contribute to the applied joint moment.

Conventional hydrostatic transmissions, which use coupled variable displacement pumps to deliver continuously variable pressure and flow, typically have a peak efficiency of around 60%. Efficiency drops dramatically away from the ideal operating point. Furthermore, a conventional system rated to absorb the full range of incident powers would be uneconomical and hopelessly inefficient in low power regimes.

In the Pelamis PTO, whenever a chamber is pressurised it exchanges fluid directly with storage accumulators; the only inefficiencies are associated with compressibility, bearing and seal friction of the hydraulic cylinders, and flow losses through valves and pipes. Careful design can set these combined losses at well under 20% over a wide range of operating conditions. The Pelamis primary transmission can comfortably absorb incident powers ten times higher than the average incident power to which the generation equipment should be economically matched. High efficiency is maintained at low incident powers, which represent much of the available wave energy throughout the year.

4. PTO simulation

A suite of numerical simulation software has been developed by Ocean Power Delivery Ltd (OPD) to verify and develop the Pelamis design and allow prediction of annual average power capture at specific sites [14].

Simulations and tank models initially assumed linear mechanical impedances at each axis (i.e. a moment is applied to each axis proportional to angular position and velocity). Control of this type is easily quantified and is straightforward to model both mathematically and experimentally. Assuming linear control and linear hydrodynamics allows frequency domain methods to be applied, offering very fast computation over a range of conditions. In tank tests, the response of the Pelamis with linear impedances has been extensively studied over a wide range of conditions, in terms of both power capture and survivability [15].

However, although modelling linear control gives great insight and continues to be useful, the hydraulic PTO applies n output moment that is subject to a variety of physical effects. It is therefore vital to gain an understanding of this quite different form of control and of the effects of real hydraulic components on machine response, power capture, and survivability. To this end, the existing time-domain simulation software was extended to include realistic control and PTO models, thus allowing development and optimisation of control algorithms in the fast, risk free, and relatively cheap virtual environment of computer simulations.

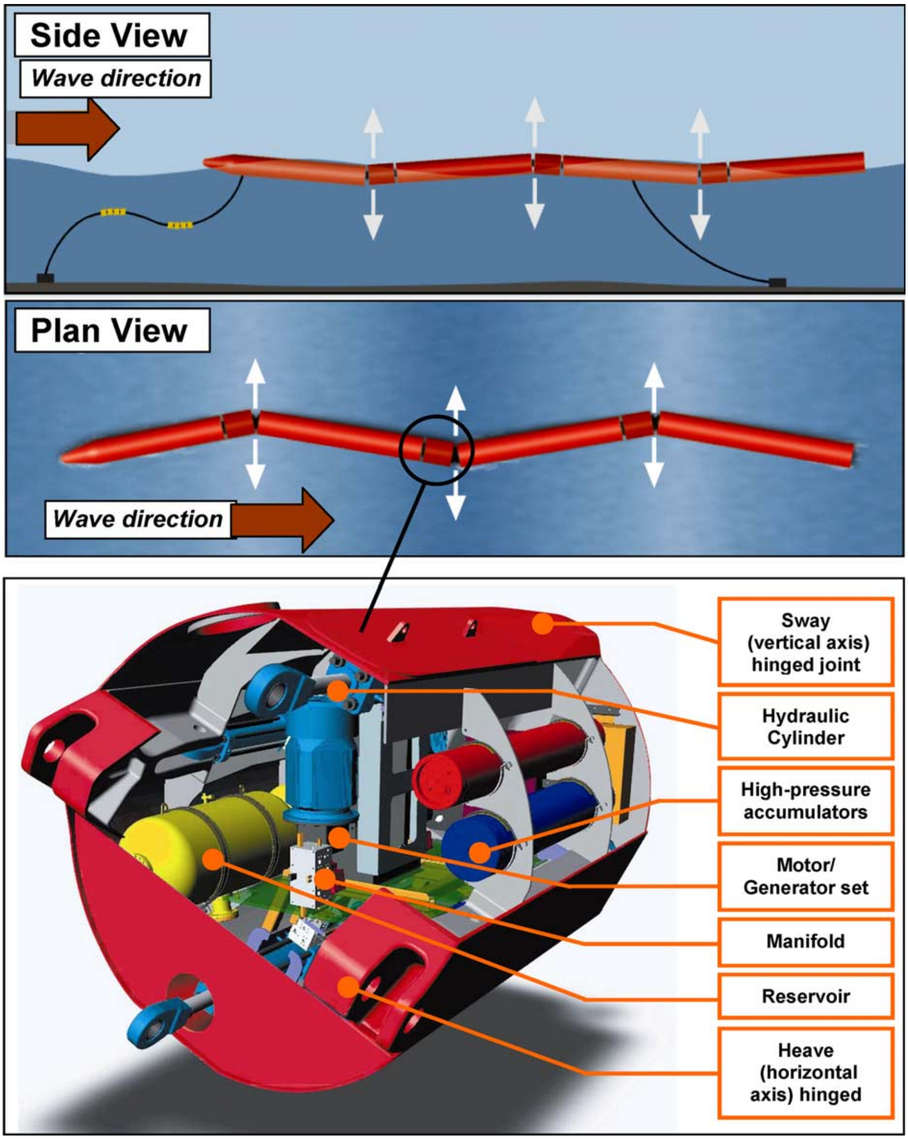

Fig. 1. Diagrams showing the response of the Pelamis WEC and the physical layout of the PTO.

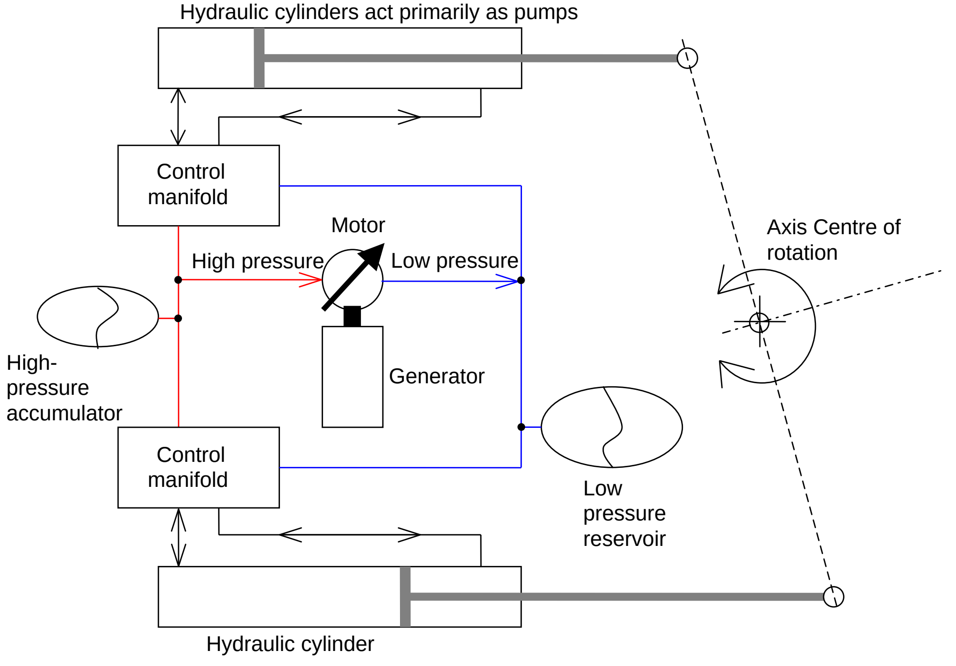

Fig. 2. Much simplified schematic of the Pelamis PTO system.

The controller and the power take-off models are programmed in separate subroutines with information passing to and from the control subroutine in the same way as for a real controller. This separation allows for the easy translation of control programmes between simulations and actual hardware.

The control subroutine samples joint angles from the existing hydrodynamics subroutines just as a real controller would sample transducer signals. A control algorithm is then applied and the output is passed to the PTO model in a similar format to the real controller. The PTO subroutine then models the physical hydraulic system and provides the resulting applied joint moment to the rest of the program. Other useful signals such as chamber and accumulator pressures and flows are also output for analysis.

Elements and effects of the PTO were treated as follows:

- Valves are modelled using conditional statements and functions relating pressure and flow. Effects modelled include: passive and active operation, cracking pressures, fluid resistance curves, and switching delays. Modelling the physical dynamics of each valve would be very computationally expensive and not result in significantly different results.
- Flow losses in pipes and manifolds are included in the fluid resistance curves associated with the valves. For example, an open valve between a chamber and the high-pressure accumulator has an associated function of flow against pressure drop including the valve cracking pressure and resistance, fittings, conduits, and piping between the chamber and the accumulator. This function is applied to the derived flow to or from the chamber.
- Accumulators are modelled using gas laws with heat transfer accounted for by applying a suitable polytropic index. This may be extended to a more general heat transfer model.

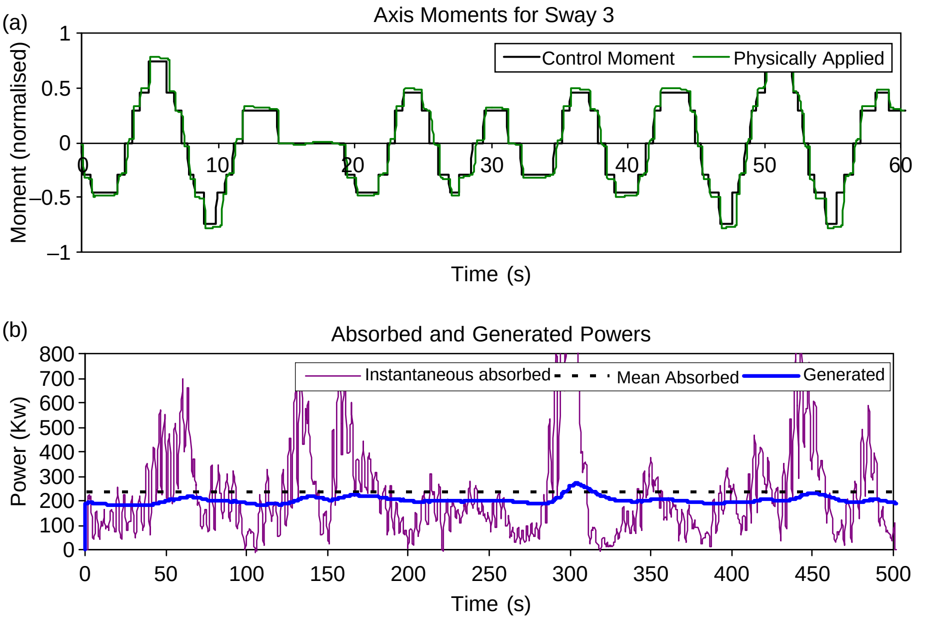

Fig. 3. Example plots of simulation output for the Pelamis operating in a typical moderate sea (a) Time-series of the moments at a single joint axis showing the moment demanded and assumed at the output of the controller along with moment that is physically applied by the PTO. The physically applied moment includes the effects of delays, compressibility, and fluid losses. The moment scale is normalised with respect to maximum moment; (b) An example plot of total power absorbed and converted to electricity (generated) over a number of wave groups. The smoothing effect of separate primary and secondary transmission is evident.

- Fluid compressibility is modelled within chambers as a volumetric spring based on a constant bulk modulus and the chamber volume on closure. An effective bulk modulus, combining the compressibility of fluid, entrained gas, and pipe work etc. is often used when describing hydraulic systems.
- Each piston seal is modelled assuming coulomb and viscous friction with a gain to represent pressure activation.
- Power generation equipment is modelled using relationships between pressure, flow, and efficiency. The accuracy of the generation model does not affect that of the primary transmission model (Figs. 1 and 2).

Fig. 3 shows some simulation output including moments from a single axis and total absorbed and generated powers from the entire Pelamis operating in a moderate sea.

5. 1/7th scale model

Early in the Pelamis development programme, a need was identified for an intermediate scale 'systems' demonstrator with which to develop and prove the full-scale Pelamis hydraulic, control and data acquisition systems. A scale of 1/7th was chosen as large enough for functionally realistic systems to be tested while remaining small enough to be tested in existing (large) wave tanks and avoid the need for specialist handling equipment.

The 1/7th scale joint systems were designed to be functionally very similar to the full-scale design with similar relative piston areas, control valves, and accumulator/reservoir sizes. This enables control algorithms developed and tested at 1/7th scale to be transplanted into the full-scale system without major changes. There are however some important differences between the hardware implementations.

The lower flow and pressure regime at 1/7th scale allows direct-acting solenoid-operated valves to be used without a piloting system as required at full-scale, where the solenoid valves act like relays to provide the hydraulic pressure to open larger valves. This simplifies the system hydraulically but makes no difference to the control system.

The 1/7th scale hydraulic cylinders are mounted externally rather than internally and connect via flexible hoses to a single manifold that houses the complete set of valves and hydraulic transducers and fixes directly to the high-pressure accumulator, reservoir, and filter. This manifold is contained in an electro-hydraulic power pack including all instrumentation, data-acquisition, control electronics and wiring.

Since, power scales with the scaling factor to the power of 3.5, the 1/7th scale prototype absorbs ~1000th of the power of the equivalent full-scale machine. No hydraulic motor-generator set is included because accurately modelling these at 1/7th scale is neither feasible nor necessary. Instead, the generation system is represented by a pressure compensated flow regulator, which dissipates stored energy as heat.

6. The 1/7th scale test rig

The 1/7th scale hydraulic system was developed and tested using a laboratory rig. The 1/7th scale PTO test rig, initially actuated by hand, was later adapted for actuation by a ball-screw operating under closed-loop control to perform the role of the waves. Pre-prototype hydraulic circuit and component test assemblies were designed and constructed for ad hoc experimentation (Fig. 4).

This work culminated in a design applied to build seven 'power pack' units, six for the joint axes of the 1/7th scale Pelamis and a spare lab test unit. Fig. 5 shows the rig being used to test and develop control software using one of the finished power packs from the 1/7th scale prototype.

The 1/7th scale test rig was used for a set of tests designed to demonstrate the operation of the Pelamis PTO, test implementations of basic control algorithms, and to verify the mathematical model developed for computer simulation. Pressure transducers were fitted to each ram chamber volume to allow measurement of pressure at every point in the system (a valuable approach later

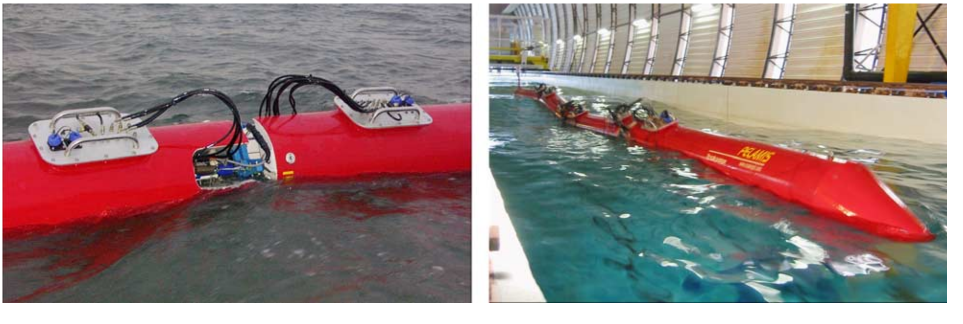

Fig. 4. Photographs of the 1/7th scale model joint during a sea-trial and the whole machine in the narrow towing tank at I'Ecole Centrale de Nantes.

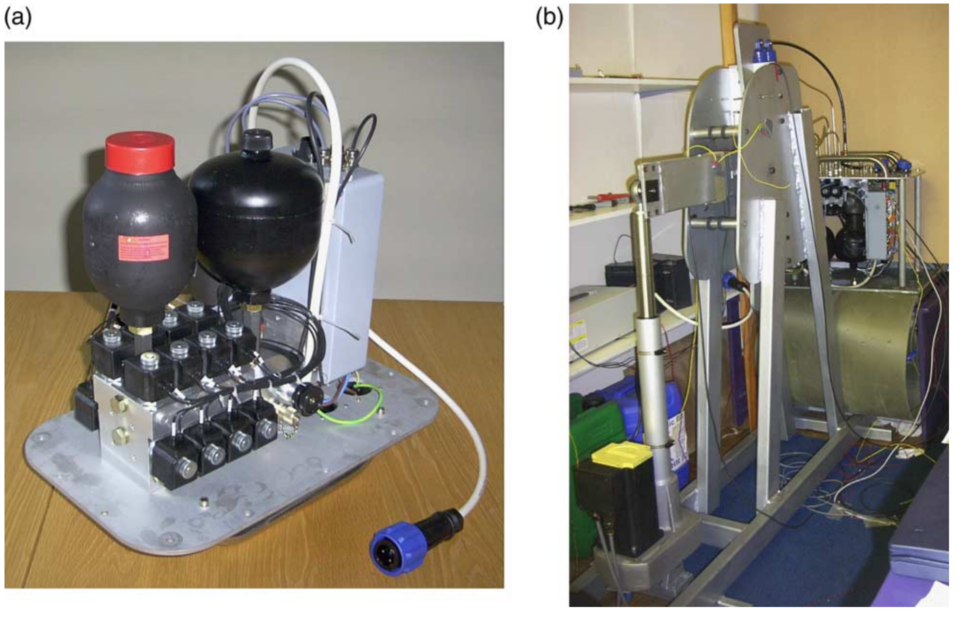

Fig. 5. (a) Photograph of a fully assembled power pack positioned upside down from the orientation in which it is installed. The hydraulic cylinders are connected to the manifold via flexible hoses fitted to ports extending through the hatch; (b) The 7th scales test rig, fitted with a ballscrew actuator under position control, being used to test a 7th scale power pack.

adopted at full-scale). Signals used by the control system, such as accumulator and reservoir pressure, and angular position, were also measured using a data acquisition system.

Figs. 6 and 7 show a time series of moment applied by the 1/7th scale PTO. Moment is also plotted against angular velocity to show the effective impedance applied by the PTO.

Each power pack has an independent controller, which when installed in the 1/7th scale Pelamis, links to a common centralised hub mounted in the nose of the Pelamis. The hub acts as the communication bridge between an external shore-based control PC and the individual joint controllers via an external Ethernet or radio modem link, as is the case for the full-scale design. Initially, all real-time control was carried out locally by the controller mounted in each power pack. This was later extended to allow real-time centralised control from the hub.

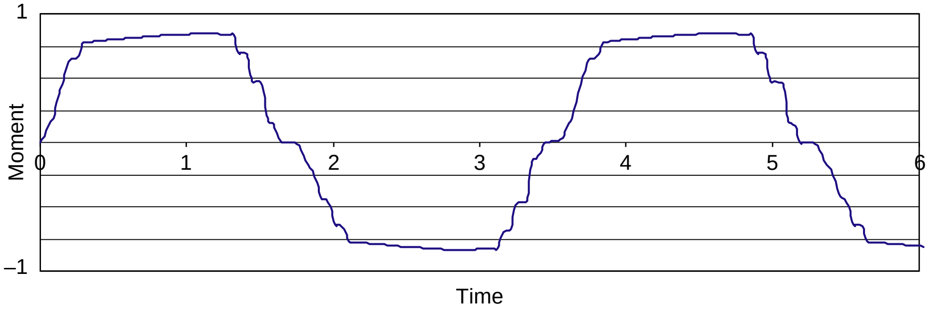

Fig. 6. A graph showing the applied moment derived by summing individually measured chamber pressures. The scale is normalised with respect to maximum moment.

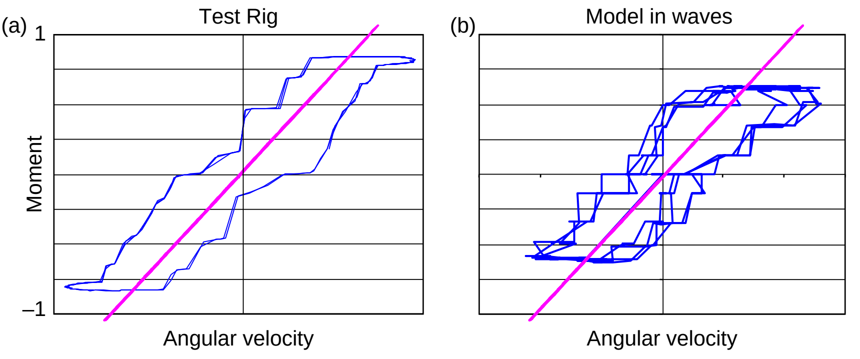

Fig. 7. (a) A plot of the impedance applied by the PTO system, derived from the applied moment in Fig. 6 above and plotted to the same moment scale; (b) The same function applied by the 7th scale Pelamis model during tank tests, also plotted on the same moment and velocity scale. The maximum moment reached is lower due to a lower operating pressure but the slope and width of the function is the same.

The 1/7th scale Pelamis first underwent sea-trials in the Firth of Forth off Edinburgh and was later tank tested at I'Ecole Centrale de Nantes, France. The results proved both the novel control and PTO concept and its implementation at the hardware and software level.

7. Full-scale test rig

After making use of a laboratory test rig at 1/7th scale, it was decided to apply a similar approach to the full-scale PTO prior to deployment on a full-scale Pelamis. A single power module, representing one of the universal joints of the Pelamis, was constructed using the same component assemblies planned for use in the full-scale prototype Pelamis. A 1 MW rated hydraulic actuation system was mounted externally to perform the role of the waves (Fig. 8).

Initially, the control system of the primary transmission was transplanted from the 1/7th scale system. After changing the appropriate parameters, the full-scale system operated as expected under the control algorithms developed at 1/7th scale. The control set-up was later swapped for a

Fig. 8. A photograph of the full-scale joint test rig.

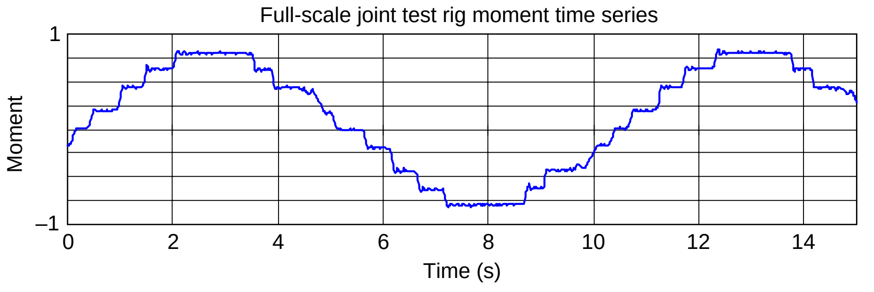

Fig. 9. Example moment time series from the full-scale joint test rig undergoing a test with sinusoidal excitation. The moment scale is normalised.

more flexible and robust distributed system based on the 1/7th scale technology. Figs. 9–11 show some results from the full-scale test rig.

The efficiency of the primary transmission was measured using the full-scale test rig by comparing the average power absorbed by the hydraulic cylinders with the constant power dissipated from the storage accumulator through a relief valve. The moment applied by the hydraulic cylinders was measured via pressure transducers in each chamber. The absorbed power at the axis could then be calculated by multiplying measured moment by angular velocity. Fig. 11 shows the instantaneous and average absorbed power of a single axis during a typical test at moderate power.

The flow rate into the high-pressure accumulator was measured by treating the hydraulic cylinders as displacement flow meters. This takes volumetric efficiency into account since only flow into the accumulator at high-pressure is measured. The high-pressure fluid transferred into the accumulator, and therefore available to the secondary transmission, was dissipated through a throttle valve at a constant rate. This power available to the secondary transmission was calculated as the pressure drop across the throttle valve multiplied by the mean flow out of the accumulator, which at steady state is equal to the mean measured flow into the accumulator.

The fluid efficiency (combined volumetric and flow efficiency) of the primary transmission, between the hydraulic cylinders and the storage accumulators, could then calculated by dividing

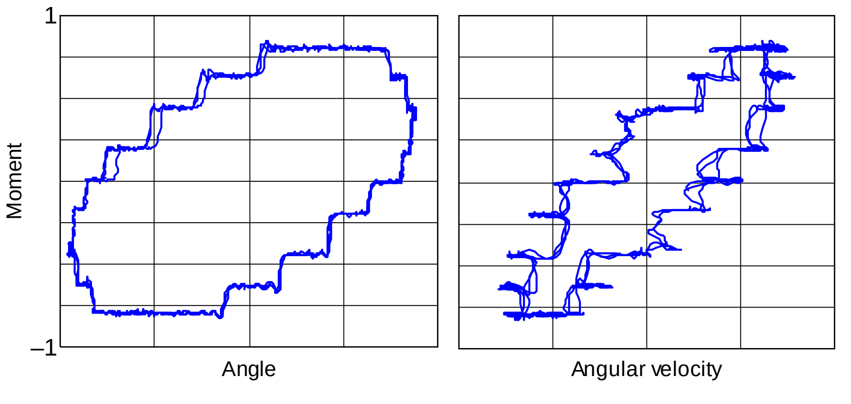

Fig. 10. Applied moment from Fig. 9 plotted on the same scale against angular position and velocity. The slope of the plot on the left gives an indication of stiffness (in this case there are no mass terms); the slope of the plot on the right approximates damping.

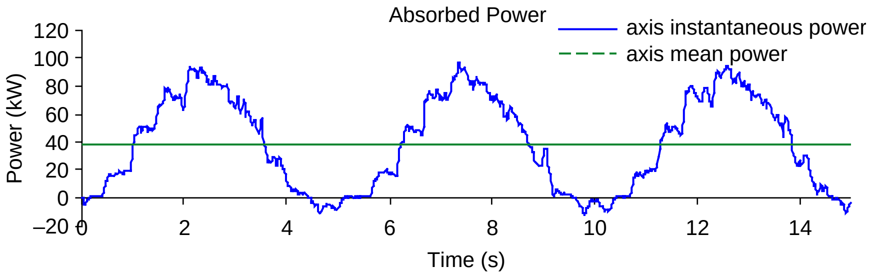

Fig. 11. Plot of power absorbed at a single axis during the same test at moderate power on the full-scale joint test rig as illustrated in Fig. 9. The instantaneous absorbed power can be seen to be negative over part of the cycle as reactive power is returned from the storage accumulator. The mean absorbed power is also plotted.

the power dissipated from the accumulator by that absorbed at the rams. The efficiency was found to be between 88 and 94% depending on the control settings, the level of peak power, and the amount of reactive power applied. These figures include the effects of fluid compressibility and flow losses through valves, manifolds, and hoses. Efficiency is expected to drop with increased reactive power as a greater proportion of the fluid flow does not transfer any net power. The losses are dominated by pressure drops across valves, manifold galleries, and lengths of hose. Additional losses due to seal friction in the hydraulic cylinders were not measured but have been estimated to be around 5%.

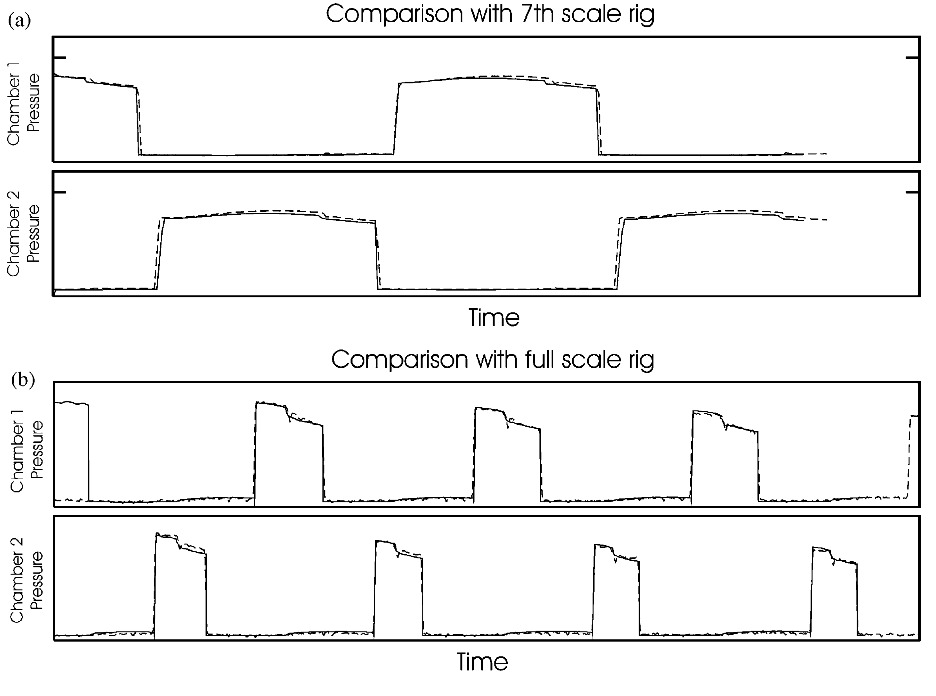

Fig. 12. Comparison of results between simulation (solid) and experiment (dashed) for (a) the 7th scale; and (b) the full-scale PTO systems running under their respective test rigs. The pressures of two chambers of a hydraulic cylinder are plotted showing the effects of real components on the chamber pressures, which ultimately determine the moment applied at the axis.

The efficiency of the primary transmission can be significantly improved by careful design of hose connections and the selection of valves for reduced flow losses. Efforts are ongoing in this regard.

Electrical generation equipment (the secondary transmission) was also tested using the full-scale rig and performed as expected with conversion efficiencies in excess of 80% over a representative range of conditions. Results are not given in this paper.

8. Simulation verification

The PTO simulation was verified using angle and control data from experiments conducted on both the 1/7th and full-scale test rigs. The simulated PTO system outputs the applied moment, flows, pressures etc. resulting from the time-series of angle and of control output recorded during the test.

Results from the computer simulation were compared with corresponding experimental results from the 1/7th scale and the full-scale test rigs. Fig. 12 shows chamber pressure time-series from the PTO simulation plotted alongside experimentally measured values. The agreement can be seen to be good. This verification of the PTO model, along with similar verifications of the hydrodynamics simulation, gives confidence in the use of simulations to predict power capture and to further develop control algorithms.

9. Conclusions

A novel hydraulic power take-off system (PTO), designed for use in the Pelamis WEC, has been demonstrated. First at 1/7th scale, then at full-scale. In each case, a laboratory test rig was used for experimentation and development. The aim of this staged development was to maximise learning and minimise risk. Each successive demonstration of the technology relied on knowledge gained and technology developed in the previous stage.

1. The PTO allows an arbitrary moment to be applied at each joint axis of the Pelamis as demanded by the control algorithm in real-time. Reactive power capability is provided to enable impedance matching to maximise power capture.
2. Separation of the primary and secondary transmissions with energy storage allows smooth output power to be generated efficiently from a highly variable input power. The generating equipment need only be rated to match a suitable range of mean incident power. The primary transmission is not practically limited in the level of instantaneous power it can capture and store.
3. A numerical model of the Pelamis hydraulic PTO has been created using conditional functions to simulate valve operation, thus requiring less computational effort than a conventional dynamic flow model using differential equations to model each element. The numerical models were verified using experimental data from the test rigs at 1/7th and full-scale.
4. Experiments have shown that performance of the PTO is as expected with combined efficiency of the primary transmission in excess of 80% at full-scale over a representative range of operating conditions. This efficiency can be improved upon through reducing flow losses by design.

Acknowledgements

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