Hydraulic Power Take-off Design for an Axi-symmetric Heaving Point Absorber

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Abstract

The FP7 'STANDPOINT' project aims to establish the axi-symmetric, self-reacting point absorber device as a viable standard approach to harvesting wave energy. In this context, the power take-off (PTO) system needs to combine survivability under extreme weather conditions and efficient, continuous power production. A hydraulic PTO system is proposed which provides means of energy storage and smoothing to decouple power output and input. A modular, maintainable and adaptable circuit design enables high efficiency of the energy conversion. Through optimisation of component layout and sizing, an appropriate compromise is found between installation space and costs on one side and the capability of harvesting power peaks on the other side. For this purpose, a combined dynamic model of the wave energy converter (WEC) system has been developed and simulated for typical sea conditions of the Portuguese test site. Simulation results have validated the viability of the hydraulic PTO design.

KEYWORDS: wave energy converter, Wavebob, Hydraulic Parallel Circuit, damping force control, modularity, power adaptation

1. Introduction

Wave energy converters (WEC) not only need to effectively convert the mechanical power of the ocean waves into grid compliant electrical power, but also to withstand extreme sea conditions for at least 25 years of operation. There is a perceptible convergence towards floating, off-shore systems that are adapted to oscillate in accordance with the incident wave climate and thus maximise energy absorption. One of such devices is the Wavebob (**figure 1**) of the heaving buoy point absorber type. The Wavebob is composed of two heaving buoys: a torus and a float linked to a submerged tank. It is kept in position using a slack mooring and it is capable of detuning from certain sea conditions by rapidly releasing the water trapped in the tank.

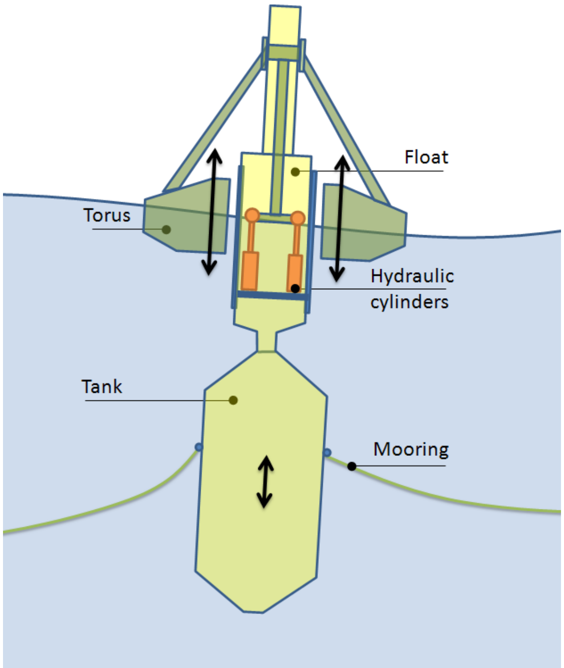

Figure 1: Wavebob principle of operation

Due to the different mass and hydrodynamic properties, the torus is characterised by a high natural frequency, while the float acts as a high-inertia body with a low natural frequency. When excited by ocean waves, both buoys respond with an oscillation of different amplitudes and phase lags, thus creating relative motion between them. Since the bodies are connected via a power take-off (PTO) system, the available energy is transformed via the PTO to useful electrical power. In addition, the forces applied by the PTO system provide damping to the relative motion, changing the response of the overall body. The ability of the PTO to adapt to the incident wave climate allows for the system to survive extreme sea conditions and increases the power capture as indicated by the instantaneous absorbed mechanical power.

PTO systems for point absorbers are generally either hydraulic [1][2] or electrical [3][4][5]. An insightful summary of the different PTO system technologies can be found in [6]. Hydraulic systems have important advantages, such as much higher force to weight ratio, energy storage and the use of proven technology. A typical hydraulic PTO system is composed of (1) a pumping module using hydraulic cylinders, (2) energy storage capabilities using hydraulic accumulators and (3) a generation module using hydraulic motors connected to electrical generators. As shown by experimental results by Henderson [1], the hydraulic energy storage has an important effect on providing a smooth power output to the grid.

Given the wide range of competing wave energy technologies [7], there is a need to identify a general set of common parameters to accelerate the adoption of agreed norms. The 'STANDPOINT' project within the European Community's 7th Framework Programme (FP7) will use the design, deployment and continuous operation of a Wavebob to develop and disseminate rules and guidelines for certification. In this EU-funded project, the Wavebob developers (Ireland) collaborate with Generg (Portugal; site and grid connection), Germanischer Lloyd (Germany; certification and guidelines), Hydac (Germany; hydraulics), and Vattenfall (Sweden; risk analysis). A Wavebob prototype is being designed to be deployed off the Portuguese coast for one year. In this paper, a novel hydraulic PTO design for this wave energy converter is proposed. For a given set of PTO requirements identified, the hydraulic PTO concept is explored in Section 2. The control system used is described in Section 3, followed by simulation results to study the influence of component sizing to the energy harvesting capability of the system in Section 4.

2. Hydraulic PTO system design

2.1. Functional and technical requirements

While wave energy resources are in average more predictable and reliable than wind, the instantaneous input power is highly irregular. Furthermore, the ratio of maximum wave input power P_{max} to average wave input power P_{avg} is extremely large.

The main challenge to a WEC power take-off system therefore is to safely endure the maximum input power peaks, and at the same time to reasonably and effectively harvest power at the predominant moderate input power levels. Survivability and good power production performance are paramount objectives to be achieved by the PTO. A systematic risk assessment procedure has been utilised to derive the main functional requirements. These have been related to the categories survivability, power production performance, operation and maintenance effort, and safety [8].

These functional requirements are used to derive the technical requirements to be fulfilled by the design and construction of the PTO system. As a main conclusion, wave energy is to be absorbed through hydraulic damping. The PTO is expected to

- provide large damping forces to guarantee survival in combination with the mechanical end-stop buffers and device structure;
- provide appropriate damping forces to tune/de-tune the oscillation and maximise power absorption.

The maximum mechanical forces to be transmitted in extreme sea states can become enormous. It is essential to separate these forces in such a way that only axial forces along the power producing degrees of freedom are channeled to the PTO.

The installed flow and force capacities are to be sized according to the expected mean annual input power and the maximum endurable force. These two objectives are contradictive and cannot be achieved at the same time. Hence, in order to optimise the damping and harvesting effect, the system must be equipped with self-tuning capabilities to make it adaptable to changing sea conditions.

A key factor for constant delivery of electrical power in grid-compliant quality is the decoupling of power output from power input. This requires some concept of storing energy. Power ripples can thus be smoothed, and power peaks can be buffered [8].

2.2. Modular power adaptation

The capability to fulfil the requirements of Section 2.1 mainly depends on the damping forces and the relative velocities between torus and float. These in turn govern the main hydraulic variables: pump flow, pump pressure, generation flow, and generation pressure. If the hydraulic circuit is bound to a single set of components, their sizing will invariably restrict the range of reasonable use to extents below the desired ones. As a result, the requirements can never be fulfilled satisfactorily, without compromising on some of the objectives that have been identified before.

Hence, a power adaptation approach is necessary to solve this problem. The modular hydraulic circuit proposed in **figure 2** comprises four sections that can be independently connected or separated through a total of seven leak-proof shut-off valves. Two pumping modules and two generation modules can thus be combined in any desired way, offering a greater variety in the selection of power producing capacity.

The required de-coupling of power output and input is achieved through establishing two separate elevated pressure levels next to the biased low pressure level (LP, 20 bar): variable pressure (VP, 20-250 bar) and high pressure (HP, 250 bar). The HP level is buffered by an accumulator and maintained through HP motor displacement control, providing a nearly constant working pressure for the hydraulic motor by compensating any variations, peaks, and ripple. Thus, the excess power of high incident waves is stored for a short period and recuperated at low wave heights. The VP level, on the other hand, is intended to provide a defined backpressure for the pumping module and thus a defined damping force. The key issues here are stiffness and controllability. Any compliance, as in the HP level, therefore is not permissible. The mode that is used to transition from LP to HP via VP is determined by the control law described in Section 3.

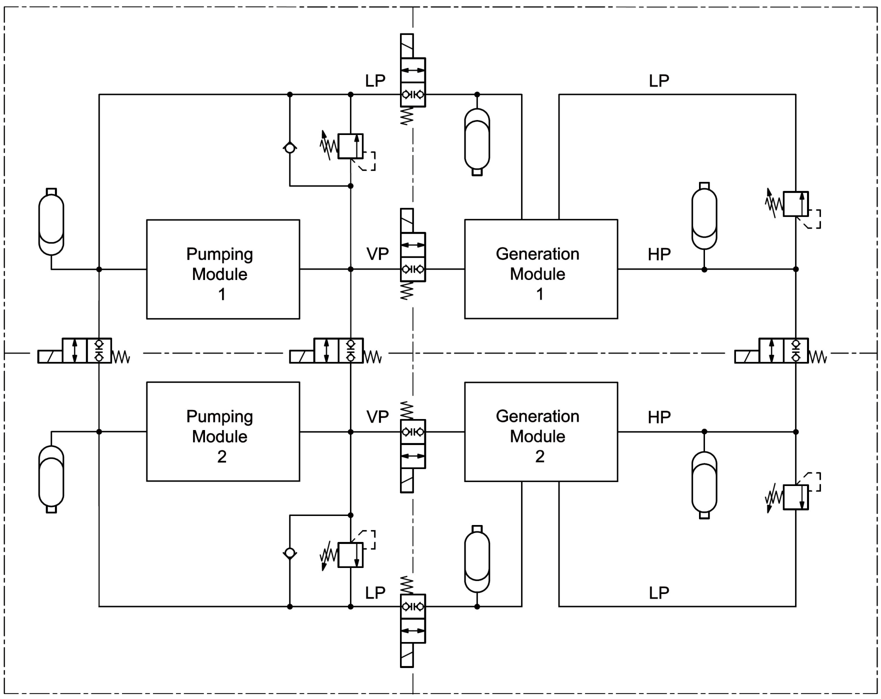

Figure 2: Modular PTO system schematic

Additionally, the modular concept is favoured by reliability, availability, maintainability and safety considerations. By sectioning off particular parts of the circuit, failures can be isolated for safe operation, maintenance, and repair. Hydraulic overload protection is provided by pressure relief valves in all VP and HP pressure lines.

2.3. Power conversion – pumping

The incoming oscillating mechanical wave power is converted into hydraulic power at the two cylinders within a pumping module, see **figure 3a**. Volumetric flows from both pumping cylinders are joined and build up the variable pressure. The design flow rate thus totals about 2.400 l/min.

Figure 3b shows the kinematical set-up of the pumping modules. The cylinders of both modules are arranged in opposite direction and differ in piston area by a ratio of 2:1, so as to allow for variable combinations of capacity. Each cylinder again has a piston/annular area ratio of 2:1. In the valve control manifold, the flow is equalised and rectified such that both extending and retracting strokes yield the same flows and pressures. By opening the pilot-operated inlet check valves in low sea states, a pumping module can be switched to by-pass mode, i.e. no flow is displaced to the VP side. In addition to the (de-)tuning capabilities through adaptable venting of the submerged tank, hydraulic cushioning and mechanical end-stop buffers provide additional overload protection and safety to avoid structural damage.

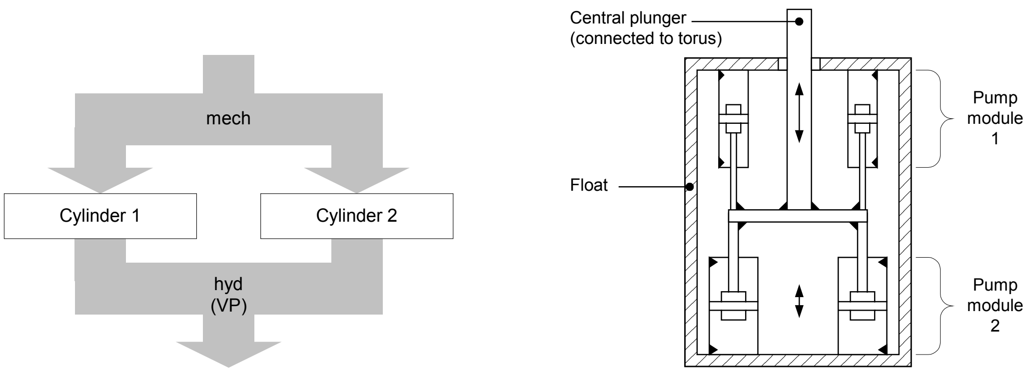

Figure 3: (a) Power flow and conversion in a pumping module (mech: mechanical, hyd: hydraulic), (b) Cylinder set-up

2.4. Power conversion – generation

The hydraulic power is converted back into mechanical power using hydraulic motors, and finally into electrical power using AC generators. Due to the buffering effect of the hydraulic accumulators, the generation module is designed for a smaller flow rate of about 800 l/min. Two concepts of power transmission and conversion have been investigated and compared in [8]: the Hydraulic Transformer Circuit and the Hydraulic Parallel Circuit (HPC), which has been identified and adopted as the superior concept.

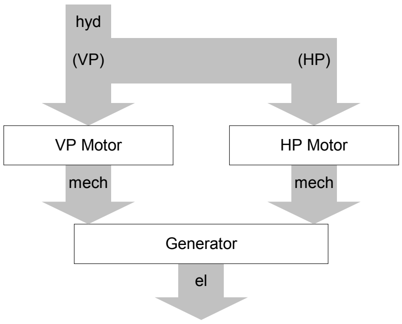

Figure 4: Power flow and conversion in the Hydraulic Parallel Circuit (mech: mechanical, hyd: hydraulic, el: electrical)

The HPC follows a parallel approach in terms of power conversion, **figure 4**. The VP and HP levels are uni-directionally de-coupled by a check valve that allows passing of excess flow from VP to HP, **figure 5**. The AC generator is driven by two variable displacement motors on a common shaft. Thus, both VP and HP sides can be used simultaneously to generate electrical power. While the VP motor displacement is ramping up and down with the wave-dependent input flow, the HP motor is used to maintain a constant generator speed. In high sea states, the motor is driven directly at full displacement by input flow entering the HP side. Excess flow is used to charge the HP accumulator, or finally throttled off at the pressure relief valve. In low sea states, the check valve remains closed, and the HP motor is driven at reduced displacement by the compressed oil volume stored in the accumulator. Constant pressure and speed conditions can be maintained within the limits set by the accumulator capacity through varying the motor displacement and hence torque and power. The lowest continuously operable sea state is thus a matter of tuning the design to the local wave climate. The control strategy that is used to control the VP and HP pressure levels via the VP and HP motor displacements is discussed in Section 3.

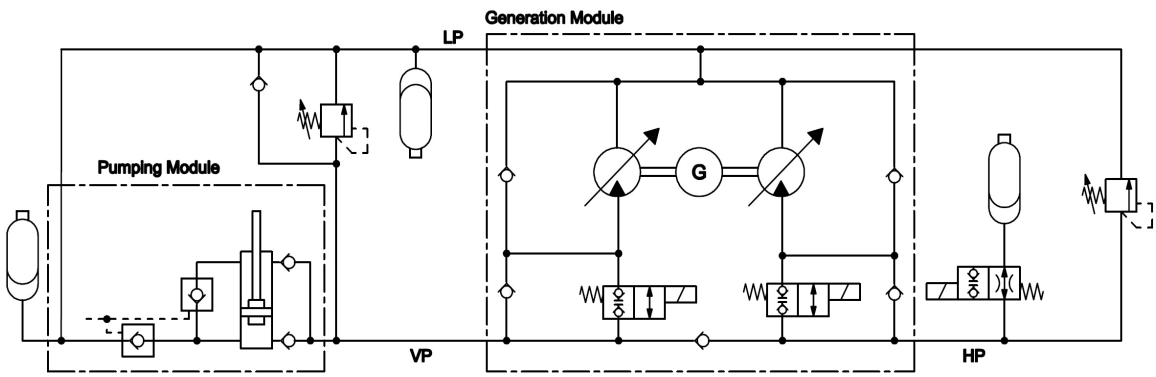

Figure 5: Hydraulic schematic of the Hydraulic Parallel Circuit

The HPC only comprises two sequential power conversion steps, passing only one rotary displacement unit. Additionally, the components of the HPC can be sized with respect to the average expected wave input power, providing increased overall mean efficiency. The maximum harvestable power is determined by the sizes of the HP motor and accumulator: a larger motor allows for greater direct power conversion, while a larger accumulator allows for longer storage periods. Apart from longer periods of calm, standstills of the rotary units and mixed-friction phases are largely avoided in the HPC. It is, however, somewhat limited in terms of realisable control laws, since it is restricted physically to certain damping force characteristics. As a PTO concept, the HPC is preferable to a direct hydraulic transmission without de-coupling due to its more appropriate sizing and smoothing. Further, it enables stiff damping force control and elastic power smoothing at the same time, while a circuit using only HP and LP levels, such as adopted in [9], can only deliver one of these advantages at the same time.

3. Damping force control

The main requirements on the damping force control are to convert energy at high efficiency, to ensure a stable motion between the torus and float, and to prevent hitting the end stops of the cylinders. There are many different approaches to maintain these requirements, see e.g. [7], [10], [11], where we will focus on a damping strategy with damping forces that are suitable (avoid part load conditions for the hydraulic motors) for the hydraulic system described in the previous section.

The damping force control has to be designed such that the oscillating power from the waves can be averaged by means of the hydraulic accumulators. However, when the pressure corresponding to the desired damping force is lower than the accumulator pressure, it is not possible to directly transfer the captured energy to the hydraulic accumulators. In this case, the VP motor is used. Due to the modularity of the hydraulic circuit, three different force levels can be attained at a particular accumulator pressure level, depending on the configuration of active pumping modules (1, 2, or 1 & 2). Considering the aforementioned, the following damping strategy is proposed.

3.1. Damping strategy

As illustrated in **figure 6**, the damping strategy comprises two phases: phase 1 with damping force proportional to the relative velocity between the torus and float and phase 2 with nearly constant damping force, depending on the accumulator pressure and the pumping modules in use. Phase 1 is used in calm sea conditions. In this operating phase there is no possibility to store energy by charging the HP accumulator. Phase 2 is used under normal sea conditions. A third phase of discharging pressure at the relief valve can be identified, but is generally avoided and not part of the damping strategy.

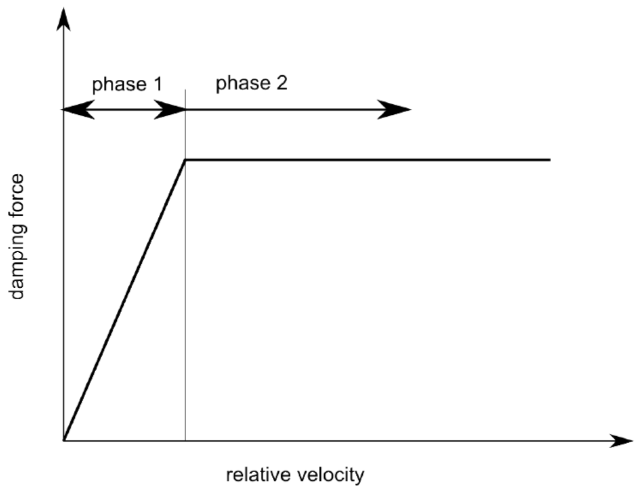

Figure 6: Damping force characteristic

3.2. Control task

The control strategy is based on two levels, top level and low level. The requirements on the top level control are mainly the forecast of the sea state in order to decide on through switching of pumping and generation modules as well as the calculation of the desired damping force. The function of the low level control is the realisation of the generation strategy, i.e. tracking the required damping force, accumulator pressure and generator power by controlling the VP and HP hydraulic motor displacements.

Based on the required functionality, the control task can be split into two different tasks, (1) the VP motor control and (2) the HP motor control.

The VP motor is used to control the desired damping force and pressure of phase 1, respectively, see figure 6. In phase 2, the VP motor is run at maximum displacement.

The HP motor displacement acts as a manipulated variable for controlling the HP motor flow rate and thus the accumulator pressure and the generated power. In this context, there are two contradictive objectives: on the one hand, constant motor torque and hence constant power delivery are desirable. However, this may imply a fairly fast and progressive discharging of the HP accumulator as the displacement is increased to compensate for the discharge pressure drop, possibly inducing the risk of a generator standstill. Therefore, on the other hand, maintaining the accumulator pressure as constant as possible is desirable in order to guarantee continuity of power generation, but will compromise the power level constancy. In the study presented here, a proportional pressure control approach has been adopted.

4. Hydraulic PTO sizing

4.1. Simulation model

In order to verify the functionality and find the optimal component sizing of the hydraulic PTO concept, a simulation model comprising the hydrodynamic behaviour of the Wavebob wave energy device, the control system and the hydraulics of the proposed PTO concept has been developed. See **figure 7** for a schematic of the simulation model.

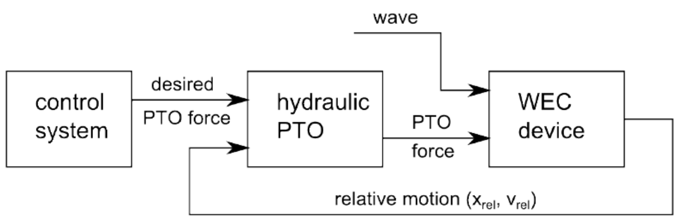

Figure 7: Schematical block diagram of the simulation model

A detailed description of the mathematical model of the system comprising the model of the hydro-dynamical behaviour of the system and the behaviour of the hydraulic system can be found in [8].

4.2. Component sizing

Within the aforementioned damping strategy, mainly two parameters are to be optimised, namely the slope in phase (1) and the set point of phase (2). The slope of phase (1) corresponds to the size (max. displacement) of the VP motor, while the constant damping of phase (2) corresponds to the accumulator pre-charge pressure and the set point for the pressure control maintained by the HP motor.

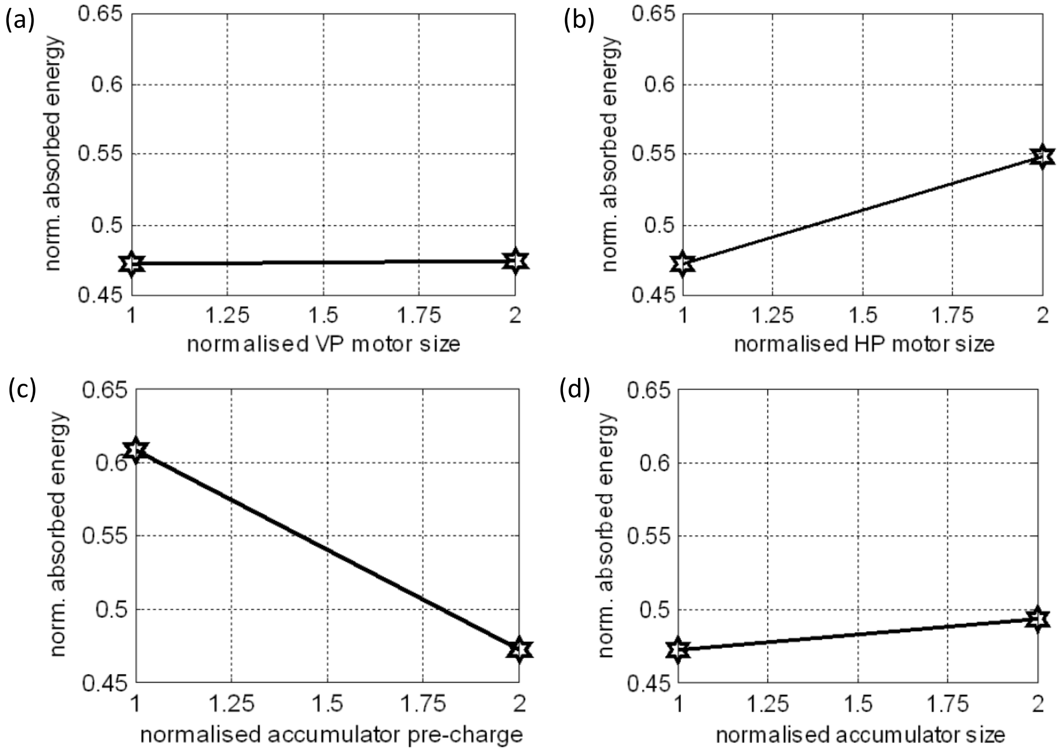

Figure 8: influence of component sizing: (a) VP motor, (b) HP motor, (c) accumulator pre-charge pressure, (d) accumulator size

In **figure 8** the influence of the parameters (1) VP motor size, (2) HP motor size, (3) accumulator pre-charge pressure, or HP motor control set point, and (4) accumulator size is depicted within a limited parameter space. The absorbed energy in figure 8 is normalised to the energy absorbed by a linear (proportional) damping strategy at approximately the same relative motion. Hence, the aim of the component sizing is to approach a normalised absorbed energy of 1 with the hydraulic PTO system. The horizontal axes correspond to the relative sizes of the components normalised to its nominal value under linear damping.

For the simulations, the wave profile shown in **figure 9** is used, which is an excerpt of the dominant sea state at the deployment site off the coast of Portugal. This wave profile corresponds to a sea state characterised by a significant wave height H_s of 1.75 m and a peak period T_p of 11.5 s (corresponding to a wave energy flux of approximately 17.6 kW/m). It is used to generate the excitation forces for the simulation results below. Although this sea state is the most representative one for the simulated deployment site, conclusions derived from the simulation results are not necessarily valid for the wave climate as a whole. Further simulation studies will be performed in order to provide a complete validation basis.

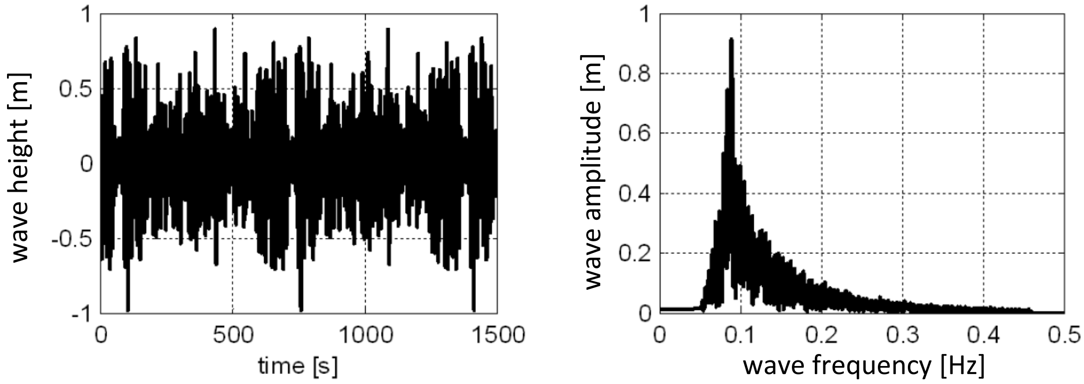

Figure 9: Characteristic wave profile and wave spectrum of the test site

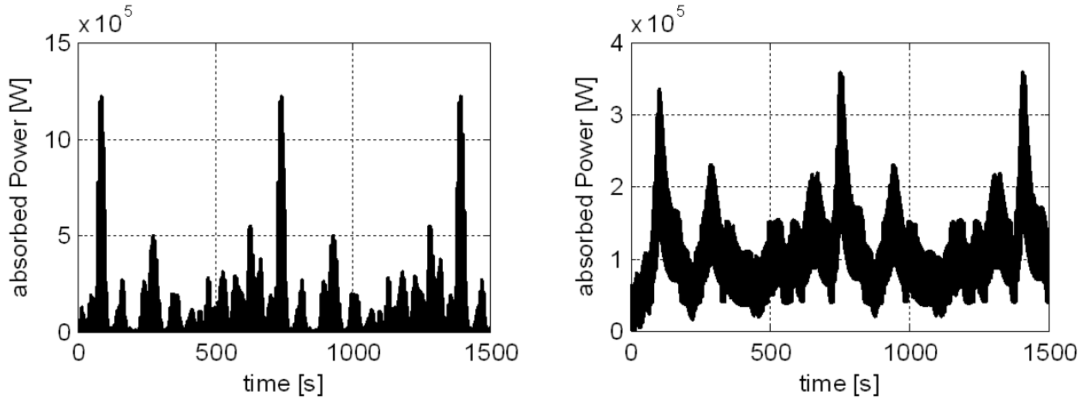

Figure 10: Output power: linear (left) and non-linear (right) damping

Utilising the combined parameter effects shown in figure 8, the absorbed energy of the hydraulic system can be maximised within the given parameter space to achieve 84 % of the linear damping benchmark case. This value corresponds to the ratio of the integrals of the non-linear and linear damping power profiles of **figure 10**. This achievement implies increasing motor sizes and accumulator size as well as reducing the accumulator pre-charge pressure. It is, however, not the global optimum, so further improvement is possible. Figure 10 furthermore visualises the power buffering and smoothing effect of the proposed concept, the power never dropping to zero.

From a technical point of view as well as from an economical point of view, it is reasonable to keep the hydraulic motors at a small size. Referring to figure 8a, the influence of the VP motor size on the energy harvesting capability of the total system is small. Hence, a reduction of the VP motor size is justifiable.

Reduction of the accumulator pre-charge pressure in contrary has a significant positive influence on the energy harvesting capability. On the other hand, this also decreases the constant damping force in phase (2) of figure 6, which has to be adjusted to the prevailing wave climate.

5. Conclusions

A novel hydraulic PTO design for a heaving buoy type WEC has been presented. The concept, using parallel power flow paths, is found to be well-suited due to the small number of power conversion steps, matched component sizing, and parallel power conversion, resulting in increased overall efficiency. The new modular failsafe design involves two pumping modules and two generator modules for high redundancy and optimised power adaptation. Accumulators are used for energy storage and thus provide a smoothed electrical power output.

A non-linear damping control approach has been tested in simulation. Numerical results for typical sea conditions have demonstrated the effectiveness of the proposed control concept. Additionally, the influence of the dominating hydraulic components (hydraulic motors, accumulators) on the energy harvesting capability has been identified which results in an understanding for the hydraulic component sizing.

6. Acknowledgment

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7. References

[1] R. Henderson, Design, Simulation and Testing of a novel hydraulic power take-off system for the Pelamis wave energy converter, Renewable Energy, vol. 31, issue 2., pp. 271-283, Feb. 2006.

[2] M. Livingstone and A. Plummer, “The Design, Simulation and Control of a Wave Energy Converter Power Take Off”, Proc. 7th International Fluid Power Conference, p. 1-13, 2010.

[3] H. Polinder, M.E.C. Damen and F. Gardner, Design, modelling and test results of the AWS PM linear generator”, European Transactions on Electrical Power, vol. 15, pp. 245-256, 2005.

[4] R. Waters, Energy from Ocean Waves-Full Scale Experimental Verification of a Wave Energy Converter, PhD dissertation, Uppsala University, 2008.

[5] M. Blanco et al., Electric Linear Generator to Optimize Point Absorber Wave Energy Converter, Proc. Of 3rd Int. Conf. on Ocean Energy (ICOE), Bilbao, 2010.

[6] S.H. Salter, J.R.M. Taylor and N.J. Caldwell, Power conversion mechanisms for wave energy, Proc. of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, vol. 216, issue 1, 2002.

[7] N. Rousseau, M. Rosa-Clot and F. Danos, Report on the state of ocean energy in Europe: technologies, test sites, and joint projects, EquiMar Deliverable D9.1, 2010, Available: https://www.wiki.ed.ac.uk/download/attachments/9142387/Equimar+D+9.1+EU-OEA-2.pdf?version=1.

[8] K. Schlemmer et al., Design and Control of a Hydraulic Power Take-off for an Axi-symmetric Heaving Point Absorber, Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC), Southampton, 2011.

[9] A. F. de O. Falcão, Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator, Ocean Engineering, vol. 34, pp 2021-2032, 2007.

[10] A. Babarit, M. Guglielmi and A.H. Clément, Declutching control of a wave energy converter, Ocean Engineering, vol. 36, pp. 1015-1024, 2009.

[11] H. Eidsmoen, Optimum Control of a Floating Wave-Energy Converter With Restricted Amplitude, Journal of Offshore Mechanics and Arctic Engineering, vol. 118, issue 2, pp. 96-102, 1996.