Design of a testing system for a power take-off unit of a wave energy converter

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ABSTRACT OF THE MASTER'S THESIS

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Wave energy means producing electricity from ocean waves. After decades of reseach, and a multitude of prototype devices installed, this renewable energy source is still globally untapped, despite its high energy production potential.

One of the design challenges in wave energy converters is the marine environment. Installing and testing devices in their actual domain is difficult and expensive. To mitigate this, the devices must be tested on dry land before deployment. Simulations and small scale experiments are vital in this process, but can only go so far. Especially, the product development of a hydraulic power take-off unit without a full scale test device is almost impossible.

This work presents the test bench of a wave energy converter called WaveRoller, and proposes a new control algorithm for the test bench. The test bench is used in the power take-off unit product development and the commercialization of the wave energy converter. In its task, it has been a vital help. 350 kW marine version of the wave energy converter and its power take-off module developed using the test bench is under construction, and will be commissioned in Peniche, Portugal during 2017. The findings of this thesis will be used to further refine the test bench, and the improved test bench will be used to develop new models of power take-off units.

Keywords: wave energy, hydraulic cylinder, power take-off, test bench, WaveRoller

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Aaltoenergialla tarkoitetaan sähkön tuottamista meren aaltoliikkeestä. Vuosikymmenten tutkimuksen ja monien testilaitteiden jälkeen tämä uusiutuvan energian muoto on maailmanlaajuisesti vielä hyödyntämättä, huolimatta korkeasta potentiaalisesta energiantuotantokapasiteetista.

Eräs merkittävä aaltoenergian suunnitteluhaaste on meriympäristö. Laitteiden asennus ja testaus oikeassa toimintaympäristössään on vaikeaa ja kallista. Tämän vuoksi laitteita tulee testata mahdollisimman pitkälle kuivalla maalla. Simulaatioilla ja pienen mittakaavan testeillä voidaan päästä pitkälle, mutta etenkin hydraulisen sähkötehontuotantoyksikön tuotekehitys on lähes mahdotonta ilman täyden mittakaavan koelaitetta. Tämä työ esittelee WaveRoller-nimisen aaltoenergiavoimalaitoksen sähköntuotantoyksikön täysikokoisen koelaitteen testipenkin, ja kehittää sitä varten uuden säätöalgoritmin.

Testipenkin tarkoitus on auttaa aaltoenergiavoimalaitoksen tuotekehityksessä. Testipenkin tulee mallintaa mahdollisimman tarkasti voimia, joita aallot aiheuttavat laitteeseen, ja tässä tehtävästä se suoriutuu hyvin. 350 kW:n mereen asennettava versio sähkötehontuottoyksiköstä on rakenteilla, ja se tullaan asentamaan 2017 Portugalin Penicheen. Tämän työn löydöksiä tullaan hyödyntämään uusien laitemallien suunnittelussa.

Avainsanat: Aaltoenergia, hydraulisylinteri, sähkötehontuottoyksikkö, testipenkki, WaveRoller

Acknowledgements

I have been working as an employee for AW-Energy for one and a half years as an automation designer, and most of my work has been developing the power take-off unit at Järvenpää test facility. For this work, the wave simulator was selected as the primary research goal. Unfortunately, the power take-off unit itself, or some subsections of it, were ruled out as a thesis subjects as they contain unpatented trade secrets. One of the challenges in this work was walking the fine line of what can be published in the thesis and what cannot.

I would like to thank AW-Energy for the chance to complete my studies during my employment, including the support for this master's thesis. Working on a new, innovative product with a relatively small development team has been a great learning opportunity, and I thank all of my colleagues from AW-Energy and other companies involved in the project.

The team at Järvenpää has been amazing to work with. Especially, I have to thank my instructor Sami Pasanen for his patient support with the thesis work. Thanks to Ilkka Pelkonen, he taught me how to properly write PLC code, could not have done it without you. Thanks to Toni Holm for his help with the measurements and Labview programming.

Thanks to my father Pekka for his support and help. His knowledge and skill in hydraulic systems made the entire Järvenpää facility possible.

Thanks to my mother Anne for the kickstart to my thesis during two-week holiday at our summer cottage, where I was able to focus on my thesis work in peace.

Järvenpää, 20.9.2016

Contents

Symbols and Abbreviations

List of Symbols

η	Displacement from still water line	m
a	Wave amplitude	m
H	Wave height, $2a$	m
T	Wave period	s
λ	Wavelength, inverse of T	Hz
$S(f,\theta)$	Directional wave energy spectrum	m^2/Hz
θ	Angle	rad
v_p	Phase velocity	m/s
v_g	Group velocity	m/s
E	Energy	J
g	Acceleration caused by gravity	m/s^2
ρ	Density (of water)	kg/m^3
J	Wave energy flux	W/m
H_s	Significant wave height	m
T_e	Significant wave energy period	s
T	Wave period	s
α	Angular acceleration	rad/s^2
ω	Angular velocity	rad/s
x	Linear position	mm
v	Linear velocity	mm/s
τ	Torque	Nm
A	Effective cylinder area	m^2
$\varDelta$	Difference	$-$
Q	Oil flow	L/min
p	Pressure (of hydraulic oil)	bar
D	Volumetric displacement	cm^3/rev

List of Abbreviations

AWE	AW-Energy Oy
BEM	Boundary Element Method
HP	High Pressure
GW	Gigawatt
LCOE	Levelized Cost Of Electricity
LP	Low Pressure
kW	kilowatt
MW	megawatt
MWh	megawatt-hours
OWSC	Oscillating Wave Surge Converter
PTO	Power Take-Off
SCADA	Supervisory Control And Data Acquisition
TW	terawatt
WEC	Wave Energy Converter

1 Introduction

Renewable energy has been in the spotlight of international attention since the evidence of global warming has become clearer during the last few decades. As the capacity to install more hydropower is limited by the availability of suitable rivers, solar- and wind energy industries have led the growth of renewable energy sector for the last decade [1]. Other untapped potential sources of renewable energy have been proposed over the years, and one of these is harnessing the energy flows contained in oceans. Sea-based energy sources have the additional benefit of not competing for land area with other potential users. The installation cost for marine devices can be an order of magnitude greater, however. Offshore wind power plants have been commercially installed since the 90's. To the general public, offshore wind farms cause less concern compared to land-based wind, and it is seen as one major advantage to offset the higher cost of commissioning for ocean installations [2].

Wave energy converters (WECs) are devices that absorb energy contained in the ocean surface waves. The industry concentrated in constructing such devices has not reached commercial success yet, and the designs for such devices have not converged to any particular model or design principle [3]. One of the major challenges faced by WECs is the harsh environment they are installed in. Offshore wind turbines reside above the water surface, and seek to minimize the effect of ocean environment on the device. WECs, however, must necessarily reside close to the water surface, as the energy resource is located there. Wave energy converters do not have the possibility of using previous designs made for land-based devices like wind turbines do.

Installing structures in the marine environment requires special equipment and methods. Installation costs for wave energy devices are high, estimated to be 20%-30% of the total capital cost of the power plant [4], and it follows that testing ocean energy devices in the actual ocean environment is very costly. Before moving to ocean testing, the technology in question must be sufficiently mature to justify such an investment. Simulational tools for wave energy have come a long way in the recent years [5, 6, 7], but the consensus seems to be [8, 9, 10] that during the design process of a wave energy converter it is mandatory to test multiple small scale prototypes to calibrate and validate the simulational assumptions.

The hydrodynamical properties of a WEC design can be tested in small scale, relatively inexpensive test, and the results gained can be applied to adjust the simulational models used for designing a full scale devices. However, the part of the WEC responsible for generating electricity off of the absorbed ocean energy, called the Power Take-Off (PTO) unit, does not scale well for smaller scale experiments[11]. This is why some WEC designers at a later stage of product development have chosen to construct a full scale test bench for the PTO module. Such test benches are usually dry tests, meaning that the PTO performance is tested in a industrial environment without water, using a drive system to emulate the movements of the hydrodynamical components of the WEC. Some wave energy developers at late stages of product development process have opted to construct a test bench for full-scale testing of their PTO systems.

The goal of this master's thesis is to present one such WEC PTO test bench.

The goal of the test bench is to verify the design principles behind the PTO, and to allow us to develop the automation system used to control the WEC ahead of marine deployment. The test bench is located in a factory hall in Järvenpää, Finland. It is currently the largest wave energy converter power take-off unit testing environment in the world.

The test bench has been built to test a novel PTO design AW-Energy has been developing for its WEC design called WaveRoller. WaveRoller is an iteration of a design concept that has been tested in various configurations for about fifteen years [12]. Wave simulator hardware was commissioned in 2014/12, and the prototype PTO being tested was initially commissioned in 2015/6. The test bench has been used to aid the product development process for the first commercial WaveRoller unit that will be deployed during 2017, at the coast of Peniche, Portugal.

The thesis consists of three parts. First part consists of a literary review that will present the theoretical basis behind wave energy, categorization of the wave energy resource and the requirement of force control for optimal power capture of WECs. Wave energy is compared to wind and solar energy due to their similar origin and capital cost structure.

Second part consists of a look at the previous device of the same basic principle that was installed in marine environment, an overview of the WaveRoller device concept, the description of its power conversion chain and the rationale behind test bench design choices made.

The third part describes the test facility, goals set for the test facility and the automation systems controlling the wave simulator, test results and recognized improvements.

2 Wave Energy

The force carried by the ocean waves has inspired inventors for centuries. The first patent was granted in 1799, and hundreds of patents were granted during 19th and early 20th centuries[13]. Despite the wide variety of ideas regarding wave energy conversion, designing a viable and economical device to harness the energies carried by the waves proved to be a challenging task.

Serious interest on the subject was renewed by the oil crisis in 1973. The raising energy prices encouraged the research on alternative, more sustainable energy generation methods. This sparked the interest among the universities and institutions in Europe and around the world to research renewable energies, and among them, wave energy. In 1974, a paper titled *Wave Power* by Stephen Salter was published in *Nature*[14]. It brought wave energy to the attention of the international community.

The fundamental theories of wave energy absorption and hydrodynamical principles governing it were developed during this period. In addition to Salter and his colleagues in the University of Edinburgh, major contributions were made by Falnes and Budal in Norway [15] and McCormic in the United States [16].

Although the theoretical work from this period is still used as the foundation for modern research, concepts for WECs from this era only reached early prototype stage of development. Lowering energy prices decreased the interest in renewable energies during the 1980's, and cuts on government funding caused a stall on wave energy research before workable, full scale devices could be realized [17].

The growing awareness of global warming and desire to reduce reliance on fossil fuels has renewed the interest in wave energy during the last 20 years [18]. Thanks to increased governmental and private funding, more than 30 projects aiming to commercialize wave energy have been kicked up. The wave energy industry is still in the R&D phase. Multiple companies have achieved grid connected power production with prototype devices, but the commercial breakthrough remains still to be seen. AW-Energy is installing its first commercial device during 2017.

The current development is focused on producing cost-effective designs for wave energy conversion. The most useful metric for assessing the energy to cost performance of various energy producing methods is the Levelized Cost Of Electricity (LCOE). This metric compares the total energy produced by a device against the total lifetime cost of the device, including installation, maintenance and decommissioning. As no large-scale wave energy project has ever been operated, financial performance of wave energy is estimated from preliminary product development power production estimations for various devices, and actual wave measurements. As the maintenance costs are largely unknown, the estimates [19, 4, 20] vary widely, placing the current LCOE of wave energy in Europe at $100 - 500€/MWh$, compared to $60 - 80€/MWh$ for land-based wind and $30 - 50€/MWh$ for coal-fired power plants. Wind energy has taken decades to reach the levelized costs it has now, so undoubtedly wave energy can also cut costs as the technology matures.

On remote islands around the world, however, the main electrical generation method is currently large-scale diesel generators that have a LCOE of about $300€/MWh$ [21]. These island locations also tend to have a large wave energy resource available.

If wave energy can prove to be reliable, it is financially feasible even at the current leveled costs.

2.1 Wave Energy Resource

Marine energy, in general, has multiple branches, each utilizing a different physical process to extract energy from the ocean. Ocean waves are oscillations of the surface water particles of the ocean, carrying the energy in the form of gravitational potential energy and kinetic energy of the moving water. Energy from tidal forces caused by the sun and moon can generally be only harvested in a limited number of locations where they create strong flows through a narrow passageway [22]. Ocean currents caused by the Coriolis effect, temperature differences and other processes can be harnessed in proper locations. Salinity difference between fresh water outlets and the ocean can theoretically be used to generate power.

Waves in the ocean are formed by multiple phenomena. Fig. 1 illustrates the sources of the waves, and the actual ocean wave form is a superposition of these different wavelengths. Wave energy industry is generally only interested in the surface waves caused by wind. Wind waves are abundant and persistent. Other natural processes can also generate waves, but those are of much longer in wavelength. These kinds of waves also carry significant amounts of energy but, due to their low frequency, are more difficult to interact with. Extremely long-wavelength waves caused by by other processes such as earthquakes or meteor strikes have enormous power, but are much too rare to be financially viable to collect, and in fact, these abnormally large and powerful waves are a design obstacle for any kind of offshore installations, including wave energy devices.

Ocean waves are generally formed by winds causing small ripples on the ocean surface which then acts as a platform for the wind to push on to. The terms *wind sea* or *storm area* describe these areas in the ocean where waves are actively growing due to the local wind. Wind waves are traveling in or close to the direction of the wind, but they contain a wide spectrum of wave lengths, with wave lengths ranging from few meters to hundreds of meters. As the waves spread out, due to wave-wave interactions and interference, most of the energy is transferred to longer wavelengths, ranging from 100 meters to 500 meters [23]. In deep water, the sea bed and other waves have negligible influence on the waves. This means that these ocean swells can travel largely unimpeded for oceanic distances.

The energy contained in ocean waves should be obvious to anyone who has traveled on a cruise ship during a storm or looked at banks of sand and stone being moved by the waves at a beach. To understand the power contained in the oscillations of the ocean surface, waves need to be quantified and their power measured. Wave heights are traditionally measured using some kind of a floating buoy or a pressure sensor to measure instantaneous water height. Plotting this against time gives a time series figure recreating the wave form in the measurement point (see Fig. 3). However, this data alone does not give much insight into the properties of the local wave climate. Some sort of statistical analysis is required to give comparable numbers to quantify the wave intensity and power levels.

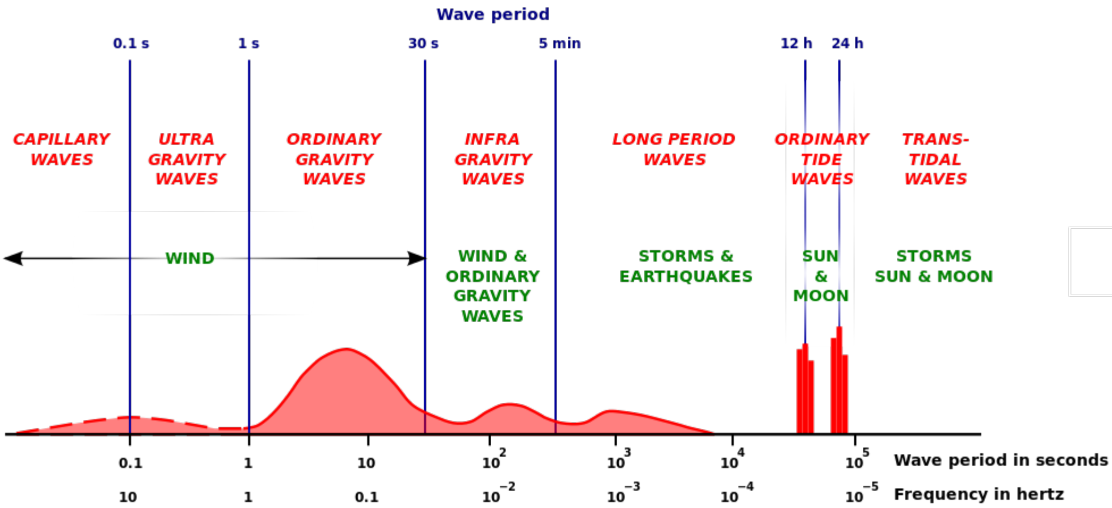

Figure 1: Categorizing water waves according to their origin, frequency domain plot. Wave category in red text, wave origin in green text. X-axis represents wave period (and its inverse, frequency). Y-axis represents the relative abundance of energy contained in waves of the given frequency. [24]

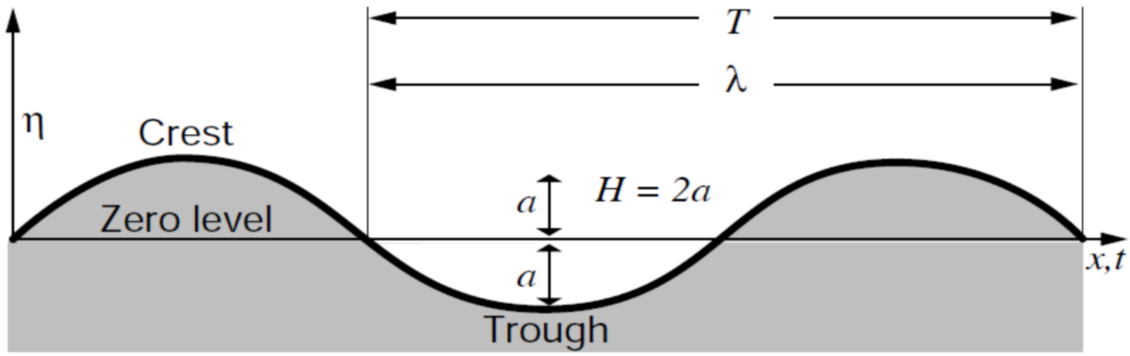

Figure 2: A simple sinusoidal wave used to illustrate the wave properties referenced in this section [25]

The convention of the offshore industry originates from the pre-computational era, where wave states were manually recorded from a surface elevation time series. Counting the heights of all the waves in a given sample, listing them in a descending order, and then selecting the highest one-third of the total waves, proved to be a simple and statistically meaningful way of categorizing sea states. Due to this tradition, the usual measure used for the *significant wave height* H_s is by definition this wave number $H_{1/3}$. The same principle applies to the *significant wave period* T_s, which is by definition $T_{1/3}$. Fig 2 offers illustration to the key parameters used when discussing ocean waves.

Making the reasonable assumption [26] of linear superposition, general sea states can be described by their directional spectral density, $S(f, \theta)$. This density describes how the energy is spread across frequencies and directions. It has the unit m^2/Hz. For simplicity, the following discussion assumes that waves are always traveling in a certain direction θ. Typical wave height measurements are time series comparing surface elevation versus time. Applying Fourier analysis to this data yields the approximate wave spectrum.

Looking at a point of the ocean, the oscillations of the surface can be approximated by the linear superposition of a large number of sinusoidal components with distinct frequencies f. Each of those sinusoidal wavetrains appears to be moving at its phase velocity

$$v_p = \frac{g}{2f\pi} = \frac{gT}{2\pi} \tag{1}$$

where T is the period of the wavetrain and g is the gravitational constant. In fact, the water particles are not traveling at all, but oscillating in place, in the case of simple sinusoidal waves in a circular motion. From phase velocity we can also calculate the wavelength.

$$\lambda = v_p\ T = \frac{gT^2}{2\pi} \tag{2}$$

The energy contained by waves is its ability to move water against gravitation. Energy per unit area is given by

$$E = \frac{\rho g H^2}{16} \tag{3}$$

where ρ is the water density and H the wave height, or distance between minimum and maximum elevation. In the case of sinusoidal waves double the amplitude, $H = 2a$. More importantly for the context of wave energy, oscillations carry energy with the group velocity

$$v_g = \frac{v_p}{2} \tag{4}$$

Multiplying velocity with energy from Eq. (3) gives us the energy flux, i.e. power, in a direction θ of

$$J = v_g\ E = \frac{\rho g^2 H^2 T}{64\pi} \tag{5}$$

which has the unit W/m. This figure signifies the power flow of a monochromatic sinusoidal wavetrain in its direction.

The spectral moments (m_n) of the spectral function are useful in quantifying the power carried by the seas. Here m_n denotes the nth moment of the frequency spectrum, given by

$$m_n = \int_0^\infty f^n S(f df) \tag{6}$$

Comparing these traditional wave measurements to the spectral approach of Eq. (6), it was found that $H_{1/3}$ is approximated by $4\sqrt{m_0}$. This justifies the usage of the traditional sea state measure H_s in the context of wave energy, but the energy carried

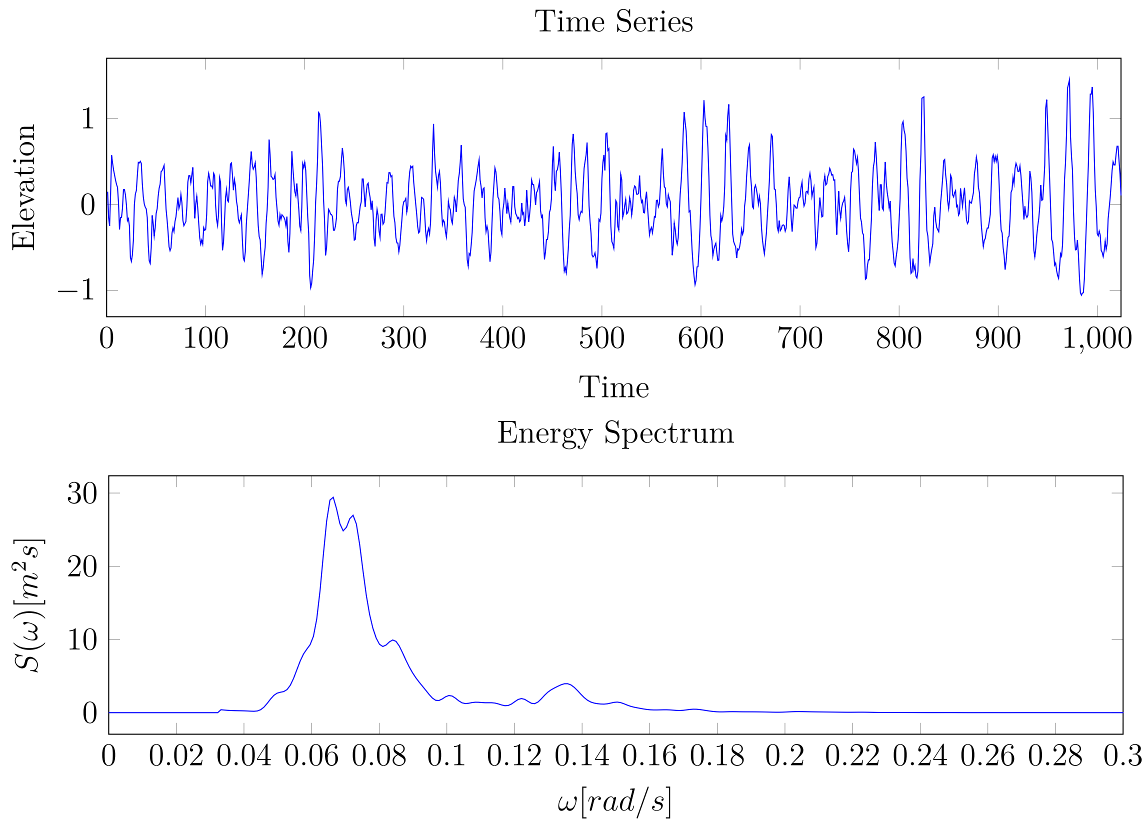

Figure 3: Wave data representation with a time series plot and a spectral plot.
Above: Time series shows the difference in wave height measurement from the still-water line per time unit.
Below: The spectral plot is the Fourier transformation of the above time series, showing how the energy content of the waves is spread across frequency components. The wave height time series was taken from sonar-based wave profile measurements done off the coast of Peniche, Portugal during 2014.

by the waves is better represented by the *energy period* T_e, defined as m_{-1}/m_0. The contrast between the wave data in time series and its energy spectrum representation is illustrated in Fig 3.

Actual seas typically have significant energy periods T_e of 5 to 15 seconds and significant wave heights H_s of 0.5 to 5 meters. Applying Eq. (5) for the example values of $H_s = 2.83m$ and $T_e = 9s$ gives an energy density of $J = 35kW/m$. As seen in Fig 4, this amount varies greatly across the globe, with annual averages ranging from less than 1 kW/m in inland seas and large lakes to over 120 kW/m on open oceans of the southern hemisphere.

Generating wave energy is more profitable in areas with a higher average. The wave energy resource is typically represented in terms of a long-term average of the power parameters, long-term annual averages spanning decades into the past being preferable. Constant wave power levels through the year are preferable to large annual variations due to device sizing. An example average wave power level in terms of the annual distribution of the sea state and mean directions is given in Fig. 7.

Real seas are also highly variable, with variations occuring in multiple time scales. In calm weathers, the power can be as low as some kW/m, and in severe storms several MW/m. Hourly ($10^4 s$) and daily ($10^5 s$) power averages vary according to weather patterns. There is a large seasonal variability in the order of 1 to 10 between in monthly averages in different seasons (10^7)[27]. Due to weather mega-trends like El Ninõ, yearly($10^8 s$) averages can even be double the long term average.

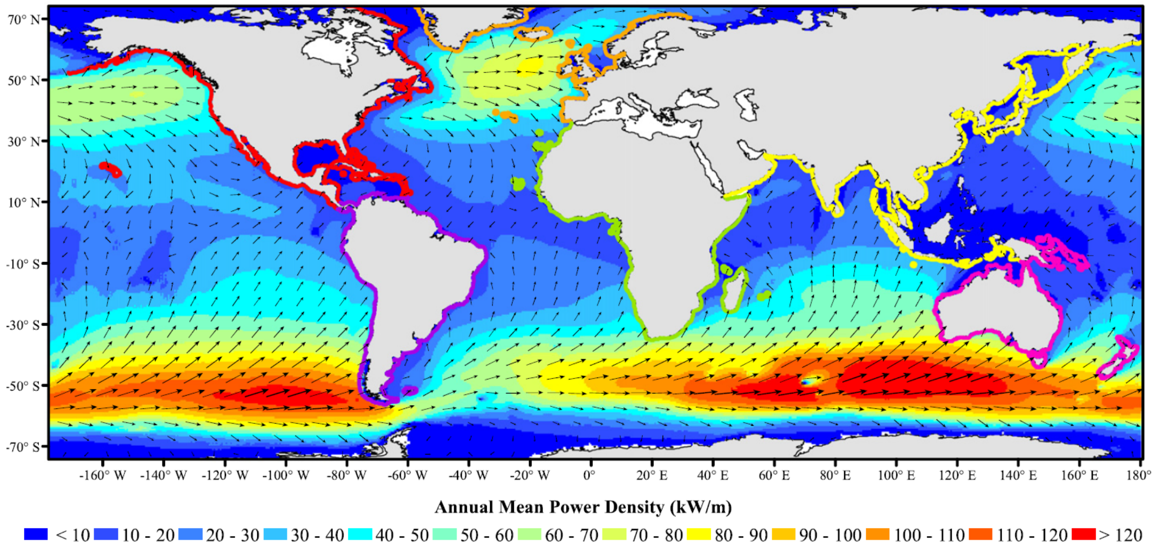

Figure 4: Annual mean wave power density (colour) and annual mean best direction ($\rightarrow$). The arrows on the figure signify the mean of the power density vectors, signifying dominant wavetrain direction. The colour signifies mean annual wave power level measured in the best annual wave direction [28]

2.1.1 Near Shore Effects

As the waves travel from the deep ocean to the shoreline, they begin to interact with the ocean floor. The orbital motion seen in deep water starts to turn more linear, as demonstrated in Fig. 5 . This strong, linear back-and-forth motion before the waves reach the shore is called the surge effect. The waves begin to slow down, with their group velocity v_g approaching zero as water height h approaches zero. It can be approximated that in shallow water, the phase and group velocities are equal, $v_g = v_p = \sqrt{gh}$. At this depth, the waves have power flux of

$$J = v_g \, E = \sqrt{gh}\frac{\rho g H^2}{16} \tag{7}$$

If the wave power level J stays constant, it would follow that as $v_g \rightarrow 0$ and $h \rightarrow 0$, then wave height H approaches infinity.

In reality, the wave height does indeed increase in shallow water, but the waves also rapidly dissipate their energy due to bottom friction. As the depth decreases

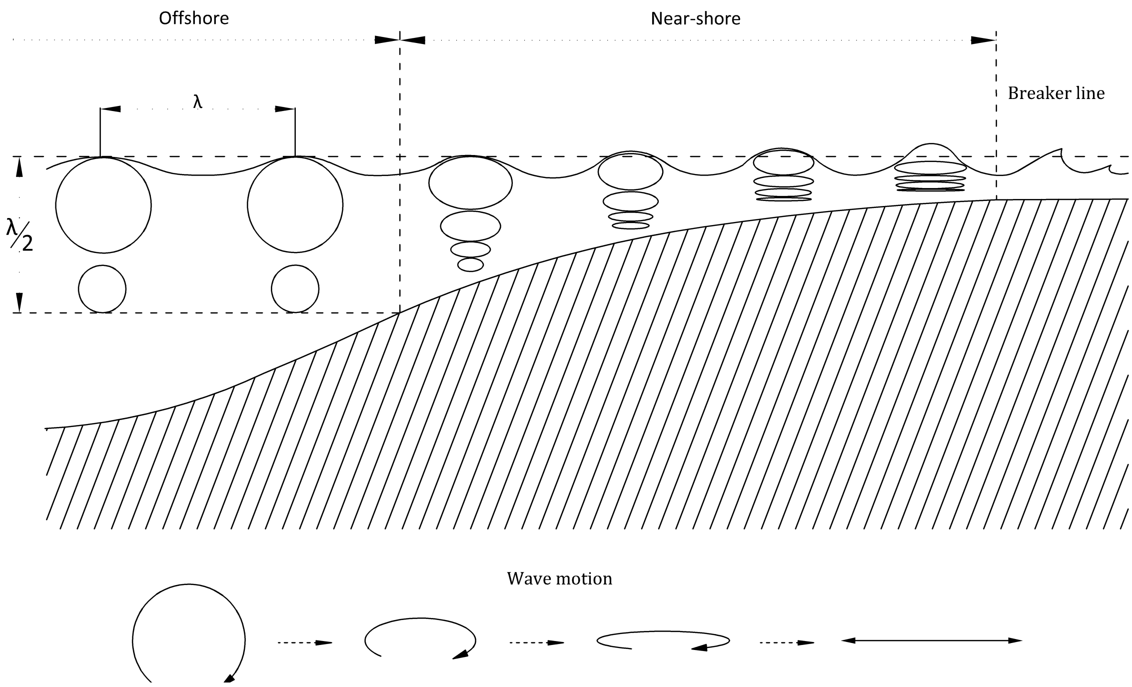

Figure 5: Interaction with the sea floor forces circular oscillations to deform, and finally break.

even more, waves reach a point where the bottom of the wave is moving slower than the top. This point is reached when the wave steepness ratio H/L becomes greater than 1/7. At this point, the faster moving top portion of the wave overruns the slower bottom part and the wave begins to break. This causes the energy still remaining in the waves to rapidly dissipate.[29]

This approximation of $v_g = \sqrt{gh}$ is valid in the region where the ratio between the water depth and the wavelength h/L is less than 1/25. Before the effects of the bottom completely disappear, there is a transitional region. At the ratios $1/25 < h/L < 1/2$, the group velocity is given by

$$v_g = \frac{1}{2}[1 + \frac{4\pi h/L}{sinh(4\pi h/L)}]\frac{L}{T} \tag{8}$$

and power flux is

$$J = v_g\ E = \frac{1}{2}[1 + \frac{4\pi h/L}{sinh(4\pi h/L)}]\frac{L}{T}\frac{\rho g H^2}{16} \tag{9}$$

Fig. 6 illustrates that in addition to waveform changes, the shore and the slowing effect it has on waves also causes other wave phenomena to take place. Waves will refract and turn to face the form of the shoreline in an orthogonal fashion. If the beach is relatively flat, waves always hit the shore from nearly the same direction, regardless of their original direction.

Table 1: Table of linear wave theory equations at different ocean depths. T is wave period, g is acceleration due to gravity, k is the wave number, and h is the wave height.[30]

	Water depth		
Parameter	**Deep -** $h > \lambda/2$	**Intermediate -** $\lambda/2 > h > \lambda/20$	**Shallow -** $h < \lambda/20$
Wavelength, λ	$\frac{gT}{2\pi}$	$\frac{gT^2}{2\pi} tanh(kh)$	$T\sqrt{gh}$
Phase velocity, v_p	$\frac{gT^2}{2\pi}$	$\frac{gT}{2\pi} tanh(kh)$	$\sqrt{gh}$
Group velocity, v_g	$\frac{v_p}{2}$	$\frac{v_p}{2}(1+\frac{2kh}{sinh(2kh)})$	v_p

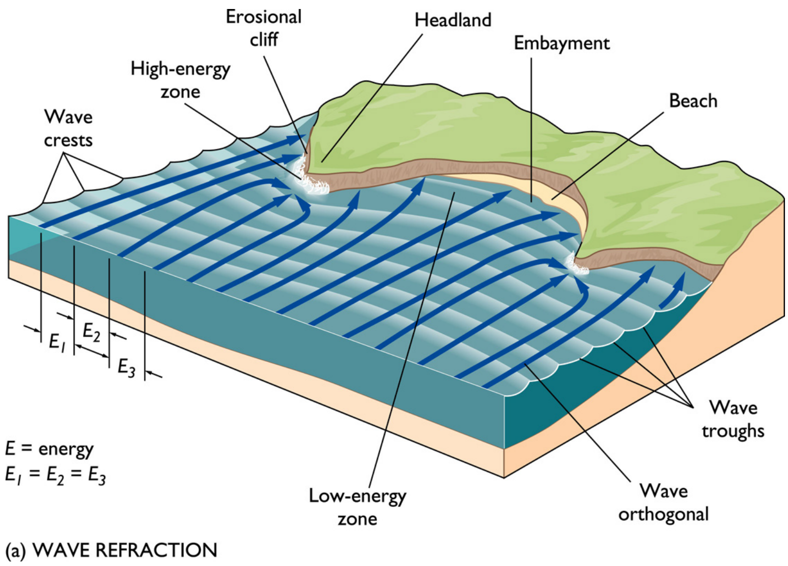

Figure 6: Illustration of wave refraction in shallow water. [99]

In very steep shores, the waves might not refract or dissipate completely, as wave reflection could become dominant.

Waves are focused and defocused by the shape of the shore, creating localized low and high energy sections in the shoreline [31].

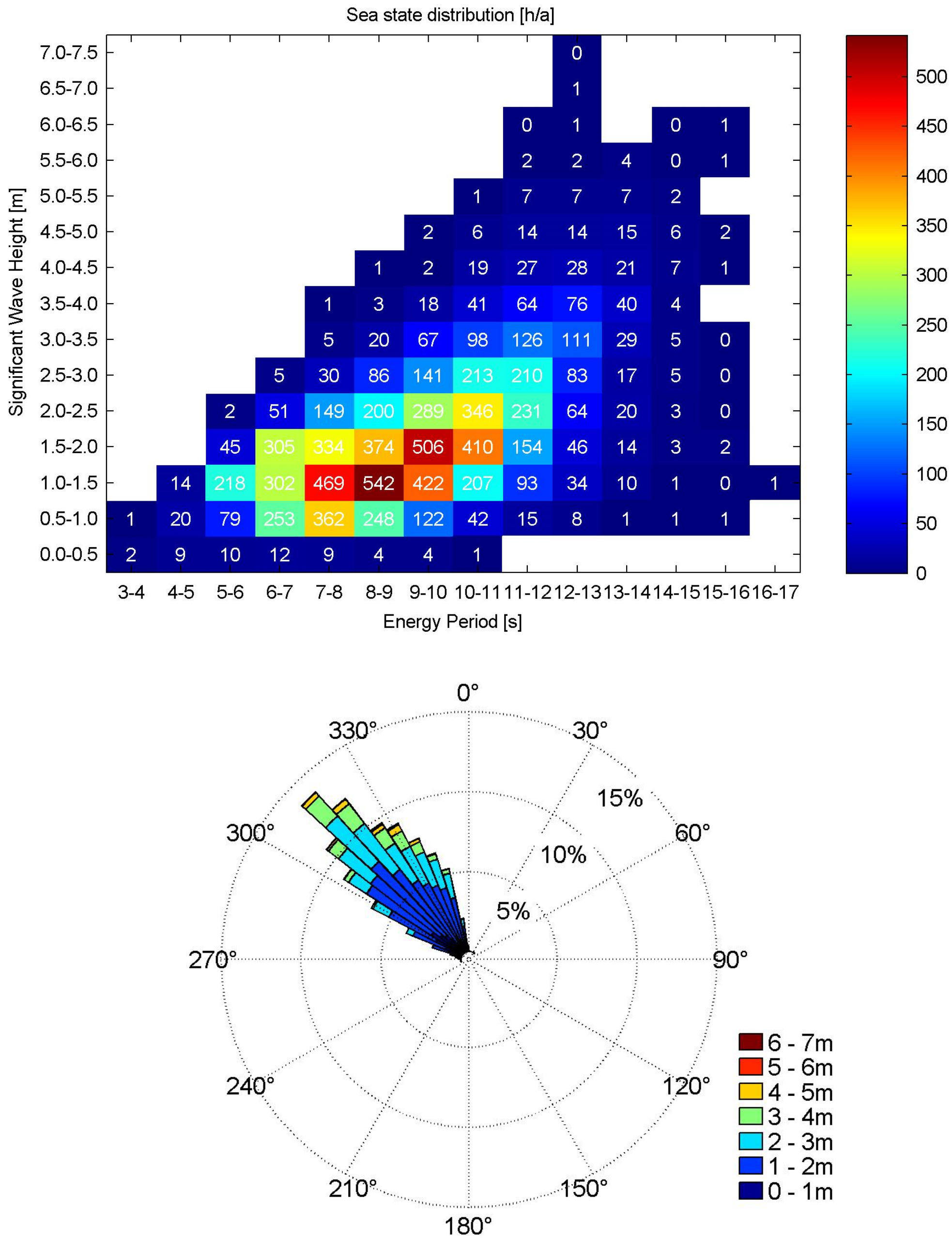

Figure 7: Wave power level visualizations. Data taken from Doppler-sonar wave height measurements performed by Instituto Hidrográfico near the coast of Peniche, Portugal during 2012-2013.

Above: Annual significant sea state matrix. Y-axis signifies the significant wave height, calculated as the zeroth spectral moment (Eq. 6). X-axis is the mean energy period. Numbers in the matrix elements signify the recorded hours when the mean sea states fell into the wave parameters.

Below: Polar plot graph from the same measurements. This polar plot called the *wave rose* shows the annual mean wave height and direction. Each bar represents a 5 degree directional slice. Bar length represents the contribution of that direction to the annual total energy. Colored chunks of the bars represent mean wave height, their distribution by direction and relative contribution to total power levels.

2.2 Conversion

If we are to extract energy from the waves, the law of energy conservation requires that we interact with the waves in a way that reduces the amount of energy present in the sea, illustrated in Fig 8. To reduce the amount of energy present, we must generate a wave that interferes destructively with the passing waves [16]. Thus, the primary conversion of wave energy is the process of reducing the energy present in the ocean by the means of radiating our own wave field that destructively interferes with the present wave field.

Absorbing energy from ocean waves and converting it into a useful format requires a body interacting with the waves. A body oscillating in water will generate waves, and given that the oscillation is in a correct phase (opposite to the phase of the passing wave), the generated wave will reduce the amplitude of the passing wave and in turn increase its own internal kinetic and/or potential energy. In other words, a body attempting to capture waves also needs to be an effective wave generator [32]. People with background in a electrical engineering can appreciate the fact that this situation is analogous with antennas interacting with electromagnetic radiation, a different type of a wave.

In the second stage, the mechanical energy captured in the oscillating body needs to be transformed into a more useful form. Through the history, many kinds of mechanisms have been suggested.

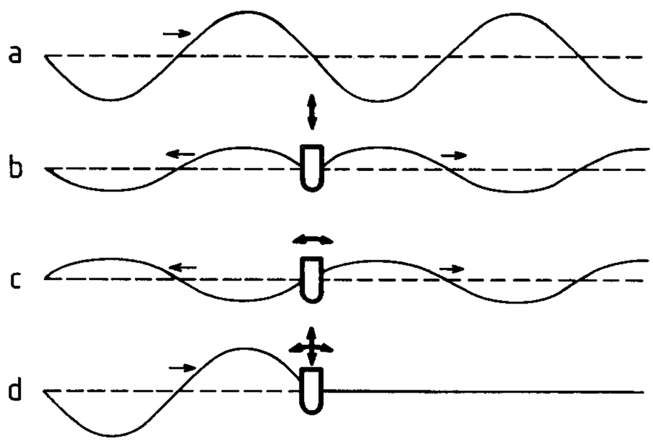

Figure 8: Illustration of wave interactions to absorb energy. Curve a represents passing wave without the oscillating body. Curve b and c represent different modes (heave and sway) of oscillation for the body. Curve d represents superposition of other three curves, with complete destructive interference.[26]

2.2.1 Mathematical Description

For simplicity, the following discussion assumes only a single mode of motion. In the more general case, the impedances, forces and speeds must be handled as matrices, and the optimum point is no longer always at resonance. However, this simplification is still mostly valid [33]. This section builds on [32], especially chapter 6.

The oscillating system formed by the ocean waves, oscillating body and power take-off machinery are analogous to a harmonic forced oscillator [26]. If we ignore friction and other losses, the power flows of the system consist of absorbed power P_a, radiated power P_r and excitation power P_e. This oscillator has some intrinsic impedance Z. The system responds to the complex excitation force $\hat{F}_e$ with the complex velocity $\hat{u}$. The force acting on the oscillator $\hat{F}_t$ can be written as

$$\hat{F}_t = \hat{F}_e - Z\hat{u} \tag{10}$$

In the frequency domain, multiplying this by the complex conjugate $1/2\hat{u}^*$ gives the time-averaged absorbed power P_a as

$$P_a = \frac{1}{2}Re\{\hat{F}_t\ \hat{u}^*\} = P_e - P_r \tag{11}$$

where

$$P_r = \frac{1}{2}Re\{Z\ \hat{u}\ \hat{u}^*\} = \frac{1}{2}R|\hat{u}|^2 \tag{12}$$

is the radiated power caused by the oscillation (R is the real part of the impedance Z), and

$$P_e = \frac{1}{2}Re\{\hat{F}_e\ \hat{u}^*\} = \frac{1}{2}|\hat{F}_e| \cdot |\hat{u}|cos(\phi) \tag{13}$$

is the excitation power from the incident wave. ϕ is the phase difference between $\hat{u}$ and $\hat{F}_e$.

As the goal is to absorb as much power from the ocean as possible, it is clear that the oscillation speed u has to be in the same phase as incoming power F_e, so that the phase difference ϕ becomes zero and $cos(\phi)$ becomes one, maximizing absorbed power in Eq. (13). This can be intuitively thought as requiring us to not push against the wave phase or to lag behind it.

The radiated power cannot be seen as a loss, as it is a necessity for wave interference and thus the capture of power.

According to Eq. (11) it is required that some amount of power must be radiated away to be able to absorb any power. Intuitively, it would make sense that the optimal way to interact with the waves would be to generate a wave that completely destructively interferes with the incident wave, and gives all of its energy not used in radiating the wave to the oscillator. As it turns out later, our intuition here is correct.

Notice that the P_r is quadratic in the oscillation velocity u, but P_e is linear. This means that there is some optimum oscillation speed u_{OPT}, where P_a is maximized. The optimal power capture is achieved when the velocity vector of the oscillator u is perfectly in phase with the incident wave fronts force F_e. As the oscillator is bound to radiate waves with power P_r to capture the incident waves power P_e , the maximum amount of captured power P_a is

$$P_a = {}^1\!/_2\overline{F_e(t)u(t)_{OPT}} = {}^1\!/_2 P_e = P_r \tag{14}$$

This means that in the ideal (lossless) case exactly half of the incoming power P_e is radiated away. Aiming to reaching this optimum is called complex-conjugate control. In actual devices, the absorbed power P_u is split between converted useful power delivered to the power take-off machinery and frictional power P_f that is lost due to viscosity, friction and other non-idealities.

2.2.2 Control

Some physical properties of the body can be changed after construction, such as buoyancy. However, such changes are likely to be much too slow to react in a wave-by-wave basis. This requires some other way to control the oscillation. This means tuning the parameters of the power take-off machinery, which provides the force F_u for the oscillating body to act against. Optimizing this force to correctly react to the incoming waves has been the primary focus since the early research in the 1970's[34]. Compared to uncontrolled power take-off, the increase in power production can be 50% or more [26, 35, 36]. This is also the most complicated area of control in these devices.

The effect of improved control for the machine force is to increase the oscillation amplitude of the device, allowing it to use as much of the structural volume of the device as possible. If the actual ocean consisted of constant frequency, monochromatic sine waves, such optimum can be calculated and the oscillator and power take-off machinery could be built to always produce optimal strokes with passive components[37], but as the real seas are highly irregular, this requires alterable, controlled machinery force.

Including non-linear, time variant power take-off power P_u requires us to move to time domain. Forces acting on the oscillating body can be represented by the following dynamic equation in terms of excursion $s(t)$ and velocity $\dot{s}(t)$:

$$(m + A_{r\infty})\ddot{s}(t) + B_f\dot{s}(t) + k_r(t)*\dot{s}(t) + Cs(t) = F_e + F_u(t) \equiv F_{ext}(t) \tag{15}$$

where the right side represents the external forces $F_{ext}(t)$ (excitation force $F_e(t)$ caused by the incident wave and controllable machinery force $F_u(t)$ acting on the system). The left side of the equation contains the intrinsic hydrodynamical parameters of the system, where m is the mass of the body, $A_{r\infty}$ the "added mass" caused by the increase in the potential energy of the body when it deforms the water surface, B_f the mechanical resistive loss force caused by viscosity and friction, C the systems buoyancy stiffness. $k_r(t) * \dot{s}(t)$ is the convolution between radiational impulse response function and the velocity of the body. The term $k_r(t)$is the inverse Fourier transformation of:

$$K_r(\omega) = Z_r(\omega) = R_r(\omega) + iX_r(\omega) \tag{16}$$

where $Z_r(\omega)$ is the radiation impedance, $R_r(\omega)$ the radiation resistance (damping coefficient) and $X_r(\omega)$ the radiation reactance of the system, representing the difference between the average values of added kinetic energy and added potential energy. Radiation impedance is a term widely used in acoustics and radio antennae technology, and as the wave-body interactions are analogous to wave energy conversion, the term is also adopted to represent the hydrodynamical properties of the oscillators in wave energy systems.

Coming back to the Eq. (14), the optimum velocity $u(t)_{OPT}$ is reached when the machinery force Z_u is the complex conjugate of the intrinsic impedance Z_i of the oscillating body, so that:

$$Z_u = -Z_i^* \tag{17}$$

In practice, this requirement of complex impedances means that our power take-off machine would need to supply power to the oscillator during some parts of the motion. Reaching this optimal motion would, at some parts of the power cycle, require instantaneous reactive power flows many times larger than the average absorbed power. Producing such power flows would likely require much more energy than the machine is able to extract on average, and thus being completely infeasible. In addition to the limited ability to provide reactive power, actual machines have finite maximum forces, and depending on the PTO implementation, limitations in the force levels they can provide.

Second complication arrives from the convolution term $k_r(t) * \dot{s}(t)$ found in Eq. (15). Our function $k_r(t)$ is known to be complex, by Eq. (16) and Eq. (17). This means that the convolution is vanishing for $t < 0$ and non-vanishing for $t > 0$. This means that supplying the optimum force becomes non-causal problem [32], that is to say that to reach the optimal oscillation we need to know the future. Intuitively, this can be understood as the requirement from Eq. (14). To always radiate with the power of exactly half of the incoming power, we will need to know the future incoming power ahead of time.

Several control strategies have been proposed to increase the power capture potential while still being implementable for actual machines. With modifications, such as using remote measurements or mathematical estimators to predict the future excitations, the causal approximations of the optimal control still run into the problem of requiring large amounts of reactive power.

2.2.3 Passive Converter

Real world machinery proposed for wave energy converters are unlikely to be able to provide much reactive power, thus restricting the load impedance to be purely resistive. A passive converter with purely resistive and time-invariant machine force is the simplest form of control, being simple to implement but inefficient, as the phase of the body motions cannot be matched with the irregular waves. Depending on the choice of the constant resistance, the body either reacts too slowly and lags behind the waves with high resistance or keeps up with the waves but absorbs very little power due to its low resistance. Targeting the most common sea states of a given site, a correctly chosen static resistive load coupled with a properly designed and sized oscillator can lead to relatively good total energy capture with a simple system.

2.2.4 Latching and Clutching Control

Latching and clutching controls are types of bang-bang control strategies that vary the machinery force between two different values. These kinds of control methods have been shown to give more optimal capture in simulations than pseudo-continuous controllers with more steps [38], while being easier to implement.

The latching controller halts the movement of the body at a certain point, usually when it stops naturally at the maximum amplitude of every given oscillation, and then releases it at a certain moment to match the phase of the wave. Machinery force can be thought to be some finite value at the power extraction phase of the motion and infinite in the latching phase. This type of control is the most researched realistically implementable control strategy, but has not seen use in actual devices apart from some prototypes, perhaps due to the complications caused by the abrupt stopping of the body and the stress caused by the large forces required to hold the body in place.

The clutching control is similar, but instead of locking the body in place, the machinery force is released at certain parts of the cycle, and then restored at an appropriate moment to match phases. Simulation results suggest that this strategy is theoretically as efficient as the latching control [39]. Setting the machinery force to zero is most likely less stressful for the PTO machinery than setting it to a potentially very high value required by latching control.

In both cases the main challenge for the controller is to determine the instant of unlatching or disengagement. No matter the control strategy chosen, determining the optimal moment to engage the machinery still remains only dependent on the future values of the incoming wave power. Non-optimal strategies giving causal approximations do exist, but regardless of the control strategy chosen, the problem remains in principle non-causal.

2.2.5 Other Considerations

A multitude of other suboptimal control algorithms for WEC's have been proposed to increase the power capture, including feedback linearisation [35], neural networks [40], model-predictive control [41] and fuzzy logic controllers[42]. However, as the implementability of these advanced algorithms is highly dependent on the machine design of the WEC [36], generalisations for the best sub-optimal control strategies are hard to make. The multitude of control strategies suggested in literature can be summed up as working well in simulations or small scale test rigs, but implementability for any full scale device remains to be seen.

As the waves in the sea are free, but complex control machinery require major capital investment [43], aiming for a simple and cheaply implementable controller might well be more economical in real devices than attempting to recreate complex control strategies theorized to be more optimal. As previously noted, moving from small scale test rigs to full scale, high power devices can radically change the dynamics of the power take-off machine. Hydraulic valves, for example, have physical limitations for their size, and as the valves get larger, the pressure losses increase radically. No scientific studies have been published for full scale devices being operated in real seas, partly due to the trade secrets of projects being private companies and partly due to the fact that such devices haven't been operated.

Comprehensive studies by AW-Energy also show that the choice of control can have a major impact on the durability of the device, further complicating the design process.

2.3 Device Classification

Unlike wind turbines, where the technology has converged to a point where everyone is making very similar rotors for large scale wind generators, no such consensus exists with wave energy converters. Hundreds of different kinds of wave energy devices have been envisioned and patented over the years, and many different schemes for categorizing them have also been suggested [44, 45, 46]. More modern classification based on the actual technologies seen as viable, or that are being actively developed, can be found in Fig. 9. In broader terms, WEC concepts can be categorized in three categories,

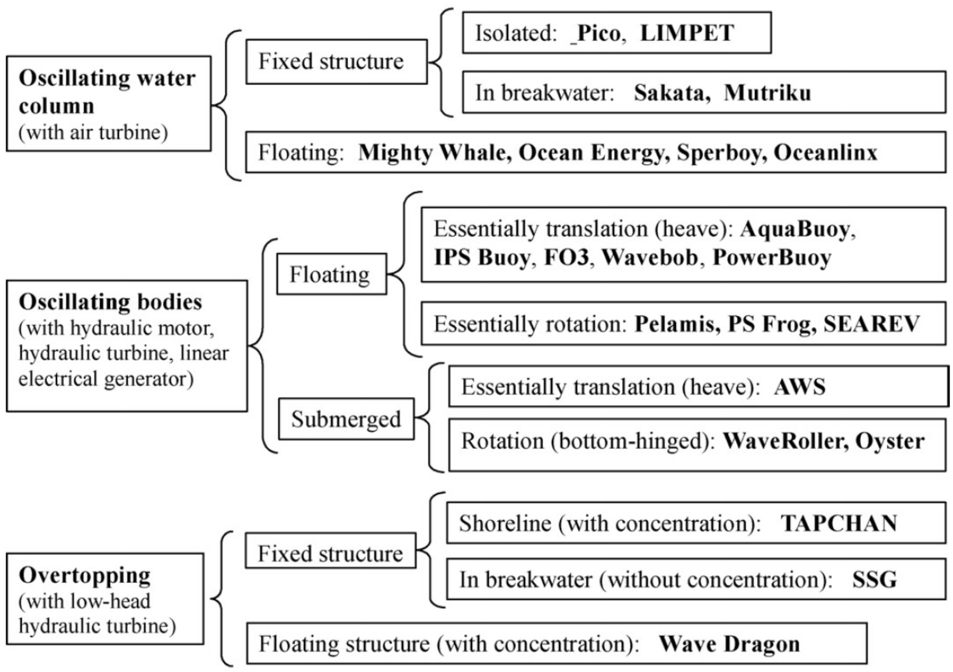

Figure 9: Classification of wave energy converters, with non-exhaustive examples of projects that have reached prototype stage or are being actively developed.[2]

Oscillating Water Column (OWC) devices contain a closed chamber with the force of rising and lowering water acting against the air inside, as demonstrated in Fig 4. The pressurized air then flows through an air turbine. The rotational energy can then be used to drive an electrical generator or other device. Devices are generally durable, and mechanically very simple to construct, [47] but are characterized by poor wave-to-grid efficiencies [46, 48].

Overtopping devices contain a reservoir of water above the sea level that is constantly replenished by the waves pushing more water over its outer walls. The water is pulled down by gravity through a hydraulic turbine or a turbine combination generating electricity. The power conversion works similarly to traditional hydro power, and can thus use established turbine designs [18].

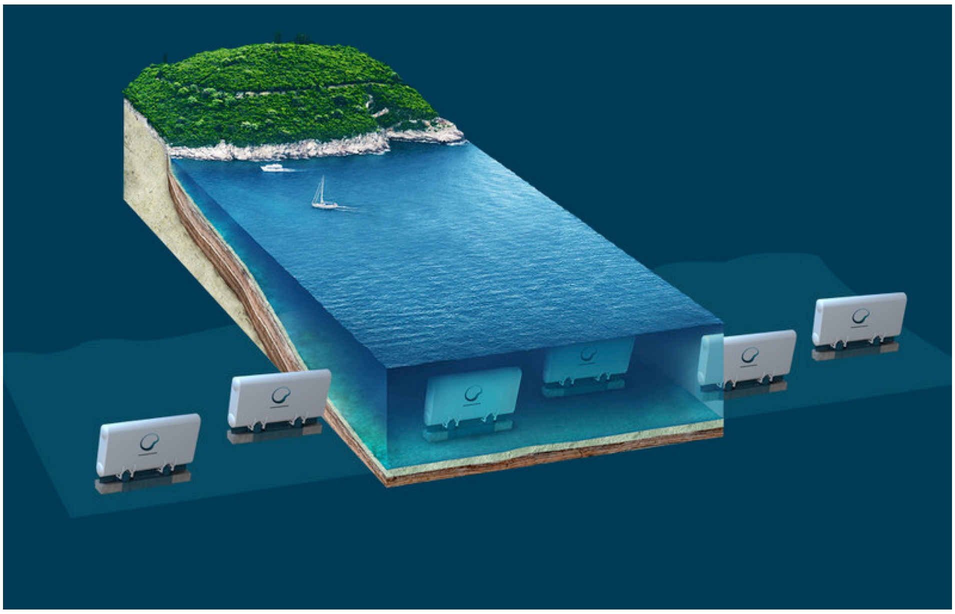

Figure 10: An artistic ineprentation demonstrating several Oscillating Wave Surge Converter (OWSC) type WaveRoller devices installed in a near shore environment. Multiple WECs installed close to each other form a wave energy farm.

Power level fluctuations are reduced by the gradual discharge of the potential energy stored in the reservoir. On the other hand, if the device is to be installed offshore, attaining high efficiencies requires very rigid mooring system [49], increasing costs greatly.

Oscillating Bodies Oscillating bodies are a broad category containing devices that have rigid structures in water, acting against the passing waves. The rectilinear or angular motion of the oscillating body is damped by a power take-off device.

Point absorber devices float on the surface of the ocean. Their internal volume is small compared to the wavelengths of the passing waves, meaning that their radiation patterns are point-like. The main mode of motion is heave, the up and down motion caused by the passing wave [50].

Oscillating wave-surge converters are terminator-type devices installed on the sea floor near the shores. As the name suggests, they mainly utilize the surging motion of the water caused by the waves interacting with the ocean floor. As the devices tend to be naturally buoyant, the heave motion also plays a part in the power absorption. The devices are typically about 10 meters by 10 meters hollow panels [51]. WaveRoller, illustrated in Fig. 10, is an example of this type of device.

Attenuators are devices installed in the direction of the wavetrain, acting mainly with the swaying motion caused by the waves.

2.4 Power Take-off

The second step of conversion is to take the mechanical energy derived from the movement of the oscillating body and to convert it to a more useful form, most often electricity. As every part of the power conversion chain has its own losses due to inherent inefficiencies, solutions with the lowest amount of intermediate steps between the oscillating body and the electrical grid would potentially offer best wave-to-wire efficiencies. Using technologies already in widespread use in other fields could lead to cheaper development costs.

Current electrical grids are based on alternating current with more or less constant voltage and frequency levels. As the waves are highly variable in power, and contain regular zero-crossings as the direction of motion changes, direct coupling to the grid would be highly undesirable, as it would cause instabilities in the voltage and frequency. Some sort of intermediate energy storage is required, and as the power conversion components induce losses, it should be as early in the power conversion chain as possible. Direct electrical conversion systems would seek to use some kind of capacitors and controllable inverters to match the power discharge with the grid voltage and phase.

A power storage has the added benefit of decoupling the two power conversion systems. Resisting the oscillator movements can be done by doing work against the accumulators, and discharging energy into the grid can be done in a smoother and more controlled manner. This allows them to be controlled independently, greatly simplifying the optimization problems.

2.4.1 Direct Electrical Generation

Almost all types of electrical generators (one important exception being solar power) are currently based on the principle of rotating magnetic fields occurring between a non-moving generator frame and a rotating shaft inside it. Some types of oscillating bodies naturally have an essentially rotating motion (OWSC and some floating bodies) and others have translational motions that would be somewhat straightforward to convert to a rotational motion using some sort of a crankshaft mechanism [52]. Using direct rotational electrical drive has been investigated [53], as it would mean a simpler coupling mechanism and less overall parts for the conversion system.

However, as wave energy is characterized by very high peak to average power ratios and rotational speeds in the order of magnitude of 0.1 Hz at very high torque, the physical size of the direct drive generator would be prohibitively large[54] and thus uneconomical. Using a mechanical gear transmission to increase the rotational speed has also been considered [55], but due to the low torque to weight ratio, the size and thus price of such gearbox would be prohibitive. Magnetic gear mechanisms could offer a more economical solution [56, 8], but are again met by the same problem of weight.

Another proposed method for direct drive electrical generation is linear electrical generation, where the magnetic fields are not rotating but move linearly in relation to each other. This would be ideal for oscillators with an essentially translational mode of motion, such as heaving buoys. Coupling the heaving body directly to the electrical generator was considered unfeasible in the past, but recent improvements in power electronics and permanent magnet materials have led to increased research in the matter [57, 58].

However, as with direct rotational generators, linear generators with sufficiently high forces are also very large [59]. Such linear generators are not in widespread use in other industries, leading to higher research and development effort requirements and novel solutions. Permanent magnets used in linear generators require neodymium, a rare earth metal that is produced mainly in China, and whose world market price fluctuates wildly [60], causing a supply chain risk.

2.4.2 Hydraulic

Another solution is to resist the motion of the oscillating body with a hydraulic cylinder. Hydraulic systems have comparatively high power to weight ratios, thus making them ideal for high peak loads seen in the ocean waves.[61] Hydraulic cylinders turn translational kinetic energy into flow of hydraulic oil. That flow can be used to drive a hydraulic motor that can in turn spin an electrical generator. Hydraulic systems offer the possibility for gas-filled accumulators that act as buffers for high-pressure oil, satisfying the need for power regulation and rectification. Simplified hydraulic system given in Fig. 11.

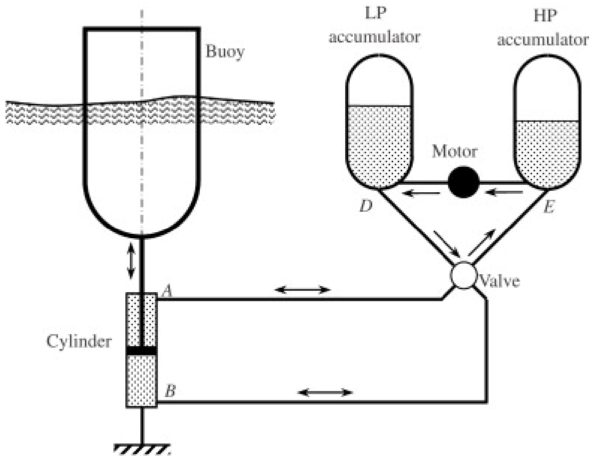

Figure 11: Simplified diagram of a hydraulic power take-off for a point-absorber buoy. [38]

Due to these advantageous factors, hydraulic power take-off is often the primary method considered for wave energy conversion[62, 13, 63]

The greatest challenge in wave energy applications of hydraulic systems is oil quality degradation combined with a very long maintenance cycle. Even with correctly designed and maintained hydraulic parts and initially clean oil, abrasive forces slowly scrape micro-particles from the metal parts of the system. These particles then further increase the scraping, leading to more and more particles over time. Metallic particles can slowly over years erode rubber seals, causing leaks or damaging other parts of the hydraulic system.This can lead to potential of leaking toxic hydraulic fluids into the ocean, even in initially sealed systems. Environmental concerns are a prime obstacle in acquiring operation licenses for wave energy devices. [13] This means that alternate layers of protection and early detection and warning systems are needed.

Hydraulic systems can typically easily provide two different pressure levels. Any more control steps would require multiple different pressure levels throughout the system, which greatly increases the complexity of the system. Implementability of a complex force control algorithm thus requires some additional machinery.

Additionally, currently available variable displacement hydraulic motors have an ideal operating point and a peak efficiency of around 80 per cent [61], and below this point efficiency drops rapidly. As incoming wave power is on average fairly low, but occasionally much more powerful, the most common sea states can have very poor total power conversion efficiencies. One suggested solution is to use multiple motors on multiple generators, and switch some of them on only during high power sea states, to allow motors to run close to their ideal efficiencies more frequently.

2.4.3 Other Considerations

The electrical energy generated by power take-off modules needs to be connected to the local electrical grid. This is likely to be done at the shore, as moving high-voltage cables and components required by efficient energy transportation across large distances to the sea would be very costly. This means that some sort of an electrical substation is required on the shore, acting as a transformer between the sea cables connected to the wave energy devices and the high voltage terrestrial cables of the electrical grid.

It seems that most people involved with wave energy have independently or otherwise come to the idea that these devices would make ideal water purifiers [57, 64, 45, 17]. Due to their location submerged in water, they have natural access to seawater. Desalinating this water via reverse osmosis and then pumping it to the shore is another potential use for the power generated by the waves, but not considered further in this work.

The idea of using the WaveRoller device for fresh water production has been investigated in a master's thesis done at Aalto University [25]. The thesis presents a review of desalination technologies, and a financial feasibility study at several potential desalination sites. The study concludes that a water desalination wave device could be a lucrative investment, but notes that the results are highly dependent on the total capital cost the device.

2.5 Device Location

Another important choice to consider is the location of the device in relation to the shoreline [13]. The choice of location are divided in three categories, mainly due to their distinct properties related to the effect of sea floor on the waves.

Offshore (usually defined as depths of 40m or more, where the ocean floor has a negligible effect on the surface waves[13]) devices are exposed to the most powerful wave regimes, and thus have the greatest potential energy generation. The visual impact and conflicts of interest with different uses for oceans are also reduced. [35] However, installation and mooring become much more expensive with increasing depth. As with offshore wind, the costs of subsea cables and cable installation becomes very significant [65]. Long distances also mean that installation and maintenance operations become more challenging.

On-shore devices have the distinct advantage of being easy to install and service, as conventional land-based techniques can be utilized. On the other hand, as ocean waves lose energy rapidly in shallow water, the energy resource available on the shore is greatly diminished. Furthermore, constructing large devices on the shoreline can cause a larger ecological and sociological response. Due to the wave interactions such as interference, some locations in the shoreline receive much greater than average concentration of wave power per width [14]. Onshore devices should be placed only on such a location, which further reduces the possible locations for installation. Oscillating water column devices and overtopping devices with fixed structures are the types usually considered for onshore installation. [44]

Near-shore placement offers a compromise between these two. Due to the energy dissipation caused by the shallow water, the maximum potential energy available is reduced. On the other hand, the most energetic waves will not reach the device, thus increasing survivability. Fixing the device to the seafloor becomes viable at these depths. This reduces the engineering complexity of the device, as mooring cables are not required. Recent comparison [66] suggests that mooring causes significant losses in energy capture compared to fixed installations. As with onshore devices, suitable installation locations are reduced by the local wave climate caused by the shoreline.

2.6 Relationship with Solar and Wind Power

Ocean waves have their origin in the wind. Winds themselves are caused by the pressure differences caused by the solar energy heating up the atmosphere. As the solar energy is converted into wind energy, the average power flow carried is increased from $0.1 - 0.3kW/m^2$ of solar radiation horizontal to the surface of the earth to $0.5kW/m^2$ kinetic energy of the wind perpendicular to the wind direction. As the wind does work over oceanic distances, the energy carried by the wind is again concentrated to $2 - 3kW/m$ carried by the waves, measured at water surface perpendicular to incoming wave front. [26] Wave energy is a small side flow of wind and solar energy, but it is more concentrated. Concentration means that a smaller surface area or volume is required to harvest the same amount of energy.

Waves are more persistent than solar radiation or wind. Annually, a coastal wave energy device installed to a suitable location will be able to produce significant portion of its average for over 80% of the time [67].

The total power carried by the waves hitting the shores of the world is estimated to be in the order of 1 TW. [68] Although this is only a small fraction of the total potentials of solar and wind power, the energy is highly concentrated. This, coupled with the fact that wave power is more persistent than solar or wind, makes wave power a tempting alternative for renewable energy generation.

Recent research suggests that wave energy is relatively predictable over the span of 1-2 days [69, 67] or even 5 days[70], an order of magnitude greater than wind powers predictability of two to five hours [71]. This opens new kinds of opportunities in balancing the energy generation of solar and wind energy with the more predictable wave energy. Predicting power input ahead of time enables utility companies to deploy their dispatch-able power reserves, solving some of the problems caused by the high variability of renewable-produced power to the power grid [72, 73].

Wave energy shouldn't be seen as a competitor to solar or wind energies, but as a third piece of the renewable puzzle, a balancing force for the more unpredictable power generation of the other renewables. The technology that wave power naturally competes against is offshore installation and remote island power generation solutions, which currently are mainly based on diesel or liquid natural gas generators. In addition to burning fossil fuels, that fuel is also hauled significant distances to the numerous offshore military bases, research facilities and island resorts around the world, further increasing costs and carbon emissions. Diesel engines are also used to power water desalination systems at these locations, where fresh water is usually unavailable.

The entire wave energy industry is still in its infancy, with nearly zero total grid connected installed capacity, as all of the currently running wave energy converters are either research or prototype devices. The potential market for the first successful device is massive. According to estimates made for the WaveRoller device, over 300 GW of financially viable sites worth of installation locations exist, translating to thousands of potential devices.

2.7 Challenges in Wave Energy Generation

The theoretical basis for wave energy extraction is well understood, and the resource shows promise for great gains in carbon-free electricity production. With decades of research and many commercial projects running, how come wave energy has yet to live up to its potential? With the recent bankruptcies of the highly funded industry forerunners of Pelamis [74] and Aquamarine Power[75] casting a shadow of pessimism over the entire industry, here are some of the challenges faced by aspiring WEC designers that need to be solved before a commercial breakthrough can be made:

- **Very high peak-to-average power and force ratios** Most of the mechanical difficulties are caused by the nature of the energy resource. [76] As the waves are slow (~0.1 Hz), stochastic high force oscillations with constant zero-crossings, filtering the power generated and transforming it to stable, 50 Hz non-fluctuating electrical energy requires very careful planning to be economical. Peak power inputs in severe storms can be ten times higher [44] than average.

- **Highly inter-disciplinary design task** spanning most if not all branches of industrial design and engineering. [57, 35] Although most of the individual components contained in these devices can be selected from offshore-proven catalogs, integrating them to a complete, wave-to-wire device has turned out to be much more difficult than anticipated.

- **Scaling up.** Many efficient and promising devices have been tested in small scale tank tests or even ocean trials. However, none of them have been successful in scaling the devices up to full scale commercial products. Many of the non-linearities and the structural and mechanical limitations associated with them are not present or not prominent enough in small scale test rigs. [13, 57] Even with careful design and simulation behind it, scaling up has brought many unforeseen challenges for the teams aspiring to commercialize their devices. Following the footsteps of wind energy and starting from small, but still commercial, devices and then scaling up to larger generator sizes and power levels is not viable, because the wave absorption efficiency is directly linked to absorber size, and sea waves having long wavelengths means that the devices are also bound to be large.

- **Financial planning.** Initial estimations for device costs can be highly optimistic, as they fail to take into account all the physical difficulties that come from working in marine environment [4] .Component prices are highly nonlinear. For example, some hydraulic components allowing two times greater oil throughput than a smaller scale solution could very well cost a hundred times more. With limited budgets, any kinds of custom-made part sizes must be avoided if used at all.

- **Cost of commissioning.** Compared to land-based prototyping work, the cost of specialized vessels and devices, and the highly specialized professionals manning them are extremely expensive. [77, 4, 18]Prototype commissioning budgets can often only afford a single marine installation operation for the device, leaving very little margin for error. Single faulty component of the prototype or a first-of-a-kind can require complete recovery, hauling to a dock and recommissioning of the entire device, leading to catastrophically increased commissioning costs.

3 WaveRoller Device

The device under development has the name WaveRoller. It is a bottom-hinged oscillating body designed to be installed on the ocean floor near to the shore, therefore experiencing the reciprocating motion caused by the shoreline interacting with the waves and slowing them down. Some writers have adopted the term Oscillating Wave Surge Converter (OWSC) to describe similar device concepts.

3.1 Previous WaveRoller Models

AW-Energy has been developing and testing oscillating wave surge converter (OWSC) designs for over ten years, and has patented the concept. The company is dedicated to the research and product development of a wave energy converter. During the infancy of the company, the innovative process ran wild, and new conceptual designs for the panel and power take-off were suggested almost daily. As the company became larger, the design began to converge towards a particular panel and power take-off design. The iterative design process has gone through many cycles of iterative product development, ranging from small, proof of concept devices built in a garage to sophisticated tank test devices and a full scale marine prototype (see Fig. 12). Small-scale tank tests have been used to confirm hydrodynamic simulation results [91].

First full-scale, grid connected demonstration device working on the OWSC principle was in operation periodically from 2012 to 2015 off the coast of Peniche, Portugal(in Fig. 12). This device was installed on top of a floating barge, capable of being submerged and resurfaced by filling ballast tanks with water or air. During operation, the barge would lie at the sea floor, held in place by gravity. The barge had 3 panels installed on top of it, with the same basic working principle of absorbing wave power from the near-shore surge effect. The barge structure acts as a containing structure for all equipment apart from the panels, protecting the systems from direct interaction with sea water.

Each panel had separate hydraulic power take-off mechanisms rated at 100 kW for a total power of 300 kW. Oil flow from panel movements was converted into electrical energy by hydraulic motors and electrical generators. The barge was connected to an electrical substation located at the beach via underwater power cable. The substation houses grid transformers and breakers, automation equipment cabins, and a control room for monitoring the process.

Goals of the previous device were to verify the principle of using bottom-mounter flaps to capture energy using the surge phenomenon found in near-shore environment. The feasibility of controlling the movements using machine force from the power take-off was the main open question. The hydraulic and electrical systems were somewhat undertuned, and the power rectification and inter-wave storage was not sufficient. The panel movements were resisted by the hydraulic motors, and thus the power generated was direly related to the hydraulic flow caused by the panel movements. This meant that the output had the same form as the incoming wave power (see Fig. 13), varying from maximum to zero at the ocean wave frequency.

Figure 12: Pictures representing earlier WaveRoller models.
Top Left: Proof of concept panel tested at Porkkala, Finland 2002
Bottom Left: Proof of concept panels with hydraulic cylinder attached, tested at European Marine Energy Center (EMEC) test facility in Orkney, Scotland 2005
Top Right: Considerably larger device with hydraulic PTO. No actual power generation, used for concept verification and panel hydrodynamics study in Peniche, Portugal, 2007
Bottom Right: Full scale 3x100 kW demonstration unit being towed towards installation site off the coast of Peniche, Portugal in 2012

From the perspective of the utility company operating the local electrical grid, this kind of pulsing power production is highly undesirable.

The device was tested in multiple different testing campaigns, separated by maintenance and modification. One of the results of the testing campaign was an external technology verification done by the certification body DNV GL, granted in 2015.

3.2 Structure of Industrialized WaveRoller

The new device, illustrated in Fig. 14, retains the same basic principle of operation. The device consists of three parts, the buoyant steel panel installed perpendicular to the incoming wave front, the foundation on which it is hinged fastened to the ocean floor, and the power take-off module housing the hydraulic and electrical systems. The PTO contains a slider-crank mechanism to linearize the rotational movement

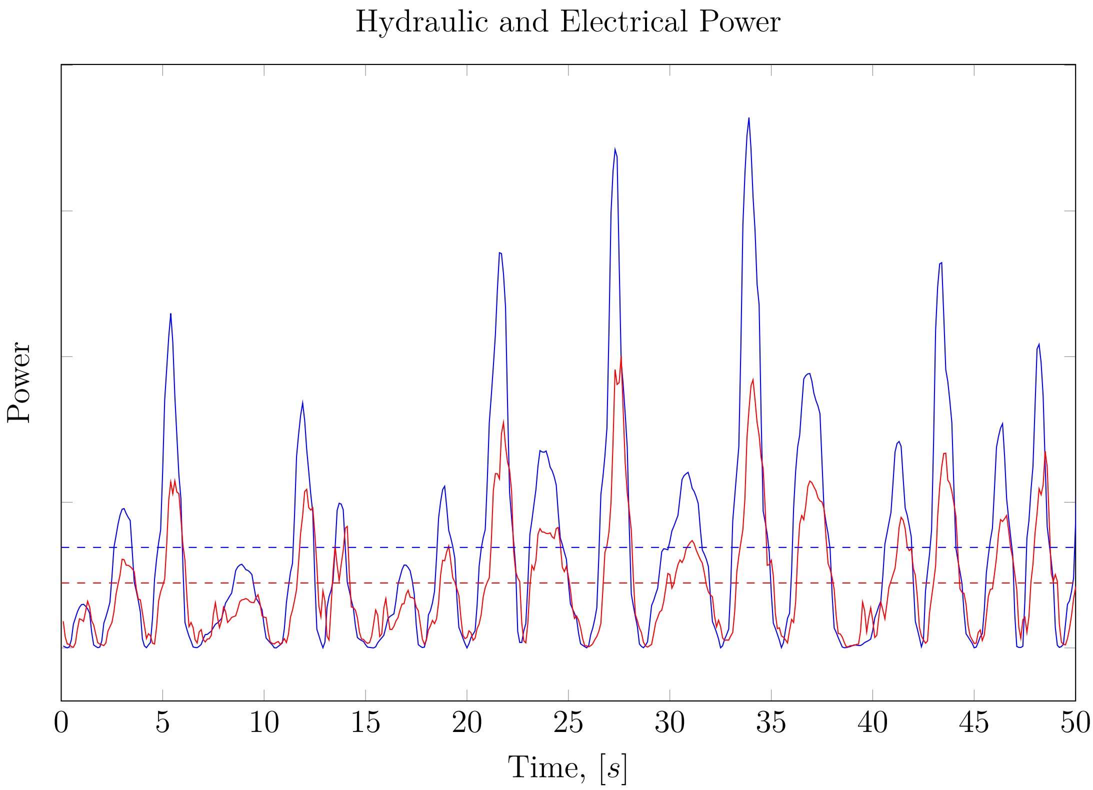

Figure 13: Illustration of the previous devices power take-off system hydraulic power input (blue line) and electrical power output (red line). The hydraulic power input is measured from the hydraulic cylinder pressure difference and the cylinder speed. The electrical output is measured from the subsea cable voltage and current. Dashed blue and red lines are the average powers of the samples, blue dashed line for average hydraulic input power and red dashed line for average electrical output. The data is taken from the operational system logs for the device, recorded in October 2014.

of the panel to linear movement of a steel shaft called the drivetrain. A hydraulic system resists the linear movements of the drivetrain with hydraulic cylinders in order to extract electrical energy from it. The oil flow is used to drive an electrical generator. This first of a kind model of the device has a nominal power level of 350 kW.

This type of oscillator design relies on the back-and-forth surge effect caused by the near-shore environment, and only partially on the up-down heaving motion that is exclusively used by many other types of WECs. This means that the device is highly sensitive to direction, rapidly losing capture efficiency if not positioned perpendicular to the incoming wave front. The panel is rigidly attached to the sea floor through hinges. This means that the panel cannot be turned to better face the incoming waves. This fact is mitigated by the re-fractioning effects of the shallow ocean floor that shapes the wave direction vector towards the coasts normal [78]. Rigid attachment to the sea floor also avoids the complication of mooring lines or other stabilizing structures needed by any floating device design.

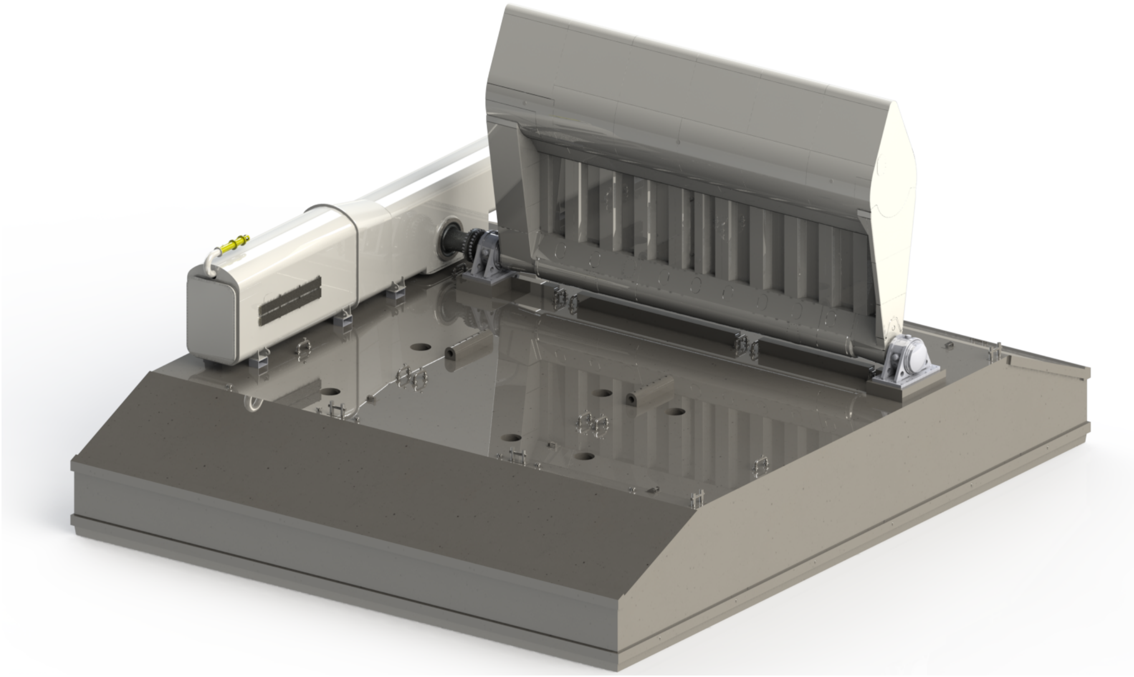

Figure 14: 3D model of the complete WEC, demonstrating the concrete foundation, the panel and the PTO.

The panel is a partially hollow steel structure. Shaping an oscillator for a wave energy converter is a delicate task. In the offshore industry, the design goal is typically to minimize the impact of the waves on the structures in order to assist their longevity and reduce material costs. Here the aim is to interact with the waves as much as possible while not exceeding structural durabilities of the materials involved. Adjusting the shape or buoyancy parameters of the panel changes it's hydrodynamical properties and responses on incoming waves. The current panel design, and indeed any panel design for WEC, is a compromise between maximal wave absorption potential, frequency response, structural integrity and monetary cost.

The rotational motion of the panel is transformed into linear motion of the drivetrain by a crankshaft mechanism attached to the panel at its hinge point. Power take-off cylinders are attached to the both ends of the drivetrain, as the waves exert similar forces in both sea and shore directions. As the drivetrain pushes into the hydraulic cylinders, the hydraulic oil flows out of the cylinder and into hydraulic accumulators. Hydraulic accumulators are a power storage mechanism that use compressible gas to store hydraulic energy. This intermediate energy storage allows for a steady flow of hydraulic power into the electrical generator.

Hydraulic motors are components designed to transform hydraulic oil flow into mechanical rotational energy. The motor is mechanically coupled with an asynchronous electrical generator. Electrical power is then fed through a subsea cable to an electrical substation at the shore. This shore substation houses the electrical transformers and protection equipment needed to couple the generator to the grid.

3.3 Test Rig Motivation

As it is difficult and costly to commission WECs in their actual operational environment (i.e. in the ocean), the designing of wave energy converters heavily relies on numerical simulations and small-scale experiments. Simulation is an invaluable tool in the initial phases of development, as it enables designers to rapidly and cheaply sift through a large number of different designs. However, the validity of these simulations should be validated and calibrated against an actual, physical system.

Tank testing, or wet-testing, means using a controlled environment to test the hydrodynamical properties of the panel. This is usually done in an indoor wave laboratory, consisting of a large pool of water and a machine capable of controllably generating waves on the water. Tank testing is widely agreed to be essential in validating and calibrating the mathematical models. Well-implemented small scale tank tests can help to identify particular problems not addressed by theoretical models. Tank tests for panels are usually done in a smaller scale. 1:25 and smaller scales are useful for model validation and proof-of-concept work. At the other end of the scale, 1:7 and larger models will bring forth non-linear hydrodynamic properties.

However, designing a scaled-down version of a power take-off (PTO) module for the WEC, that would accurately model the full-scale behavior, is difficult. It would provide poor analogy to a full-size PTO device due to non-linear effects in the power chain. For the purpose of testing the hydrodynamics of the wave absorber, a simplistic, passive PTO emulator is likely to be sufficient, but this offers little support for the PTO development process itself. This is why most companies at the late stages of product developement have constructed a test bench for their PTO design.

The power conversion chain offers many potential points for a test bench to target. An optimal solution would be to test the entire device, with panel a submerged in a controlled wave generator water tank with the PTO attached, in 1:1 scale. This is, however, unfeasible due to the space and power requirements of such testing tank and wave generator. Tank testing the PTO together with the panel in full scale would be preferable, as it would provide actual unit testing for the entire hydrodynamic, mechanical, hydraulic and electrical assembly. As the panel size increases, however, the number of possible tank testing sites rapidly decreases, and the cost of prolonged testing periods quickly becomes prohibitive.

3.4 Modeling the Power Conversion Chain

Converting the power present in the ocean to electricity at the shore ought to contain multiple power conversion steps, illustrated in Fig. 15. Modeling the entire chain of energy flow from the wave energy resource to the electrical grid is known as wave-to-wire modeling. A recent review paper [79] gives an exhaustive overview of existing wave-to-wire models, and we adopt here the classification of power conversion steps used in it.

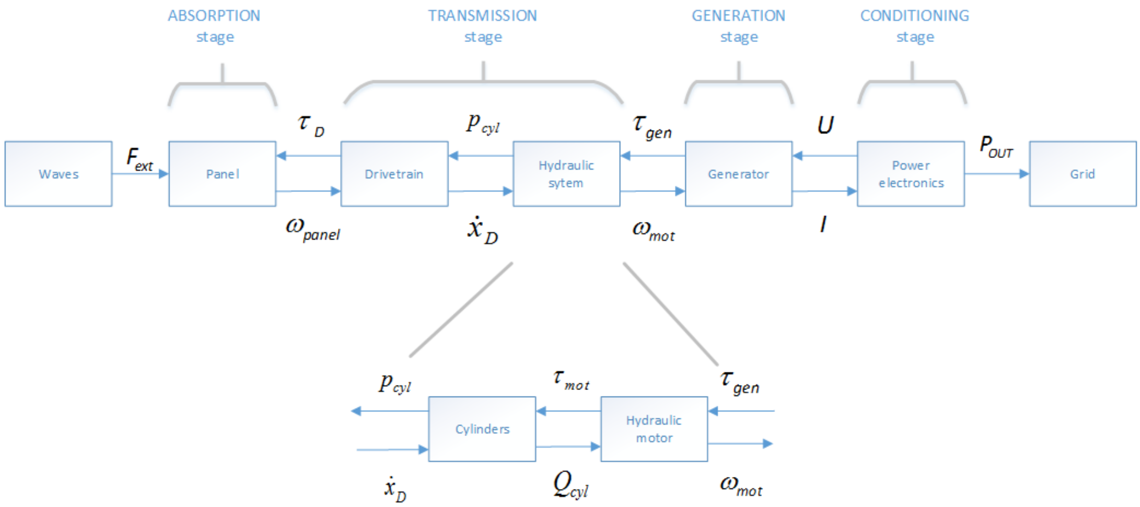

Figure 15: Power conversion chain of the wave energy converter, highlighting the power flows and the forces resisting them at various conversion steps. Redrawn and adapted from [79].

Fundamentally, the path from wave motion to usable electrical energy can be divided into six parts. The wave resource itself, the body interacting with the ocean surface to reduce energy present in it, the transmission mechanism used to resist the motion of the interacting body, the eletrical generator used to transform other types of energy into easily transportable electrical energy, electrical equipment used as an interface between the local electric circuit and the grid, and the electrical grid. Not all devices contain every one of these components, and for most, some parts are divided into physically diverse component.

For the Waveroller device, the transmission mechanism is divided into a drivetrain mechanism and a hydraulic system. The drivetrain mechanism converts rotational movement of the panel at its hinge to translational mechanical energy of the shaft. Hydraulic system is further divided into a cylinder generating hydraulic oil flow and a hydraulic motor consuming the flow. The hydraulic system also contains valves used to control pressure and oil flow, and an accumulator system used as an intermediate energy storage.

The wave energy resource itself can be quantified using the techniques described in the introductory chapter, and it is not further discussed here.

3.4.1 Absorption

The device captures kinetic and potential energy contained in the ocean waves. This flow of energy is captured by a bottom-hinged panel. As the waves generated by the panel moving in the ocean interfere destructively with the incoming wave front, power is transferred from the ocean into rotational mechanical energy and hydrostatic potential energy of the panel.

According to Newton's second law, the forces acting on the panel must be equal

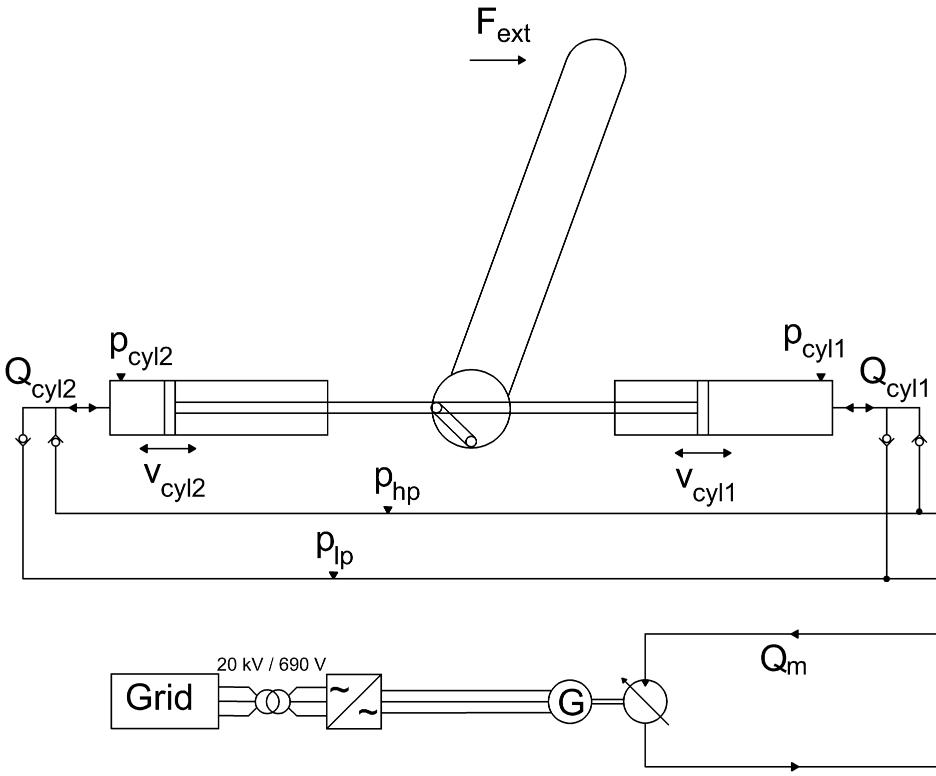

Figure 16: PTO principle shematic.

to the external forces acting on it. Placing the power of the panel on the left and wave interaction on the right can write

$$\alpha_P \; \underline{\mathrm{I}}_P = F_{hyd} + F_d \tag{18}$$

where F_d is the hydraulic force caused by the drivetrain, and F_{hyd} is the hydrodynamic force caused by the wave front including viscous and losses caused by the wave-body interaction. On the left side, α_P is the angular acceleration of the panel and I_P is the moment of inertial. As the panel is interacting in two modes of motion relative to the apparent wave front direction (surge and heave), $\boldsymbol{I}$ is 2x2 matrix. According to (15), the elements in the moment of inertia are dependent on not only the mass and the shape of the panel, but a function of panel angle, panel velocity and the convolution between panel velocity and its radiational impedance.

Modeling the hydrodynamcis using a linear model has been the standard for offshore industry, using boundary element method (BEM) to solve the hydrodynamics of the panel. Linear models assume small waves, small motion amplitudes for the absorbing body, constant hydrodynamic coefficients, and no viscous effects. However, as the objective of wave energy is to maximize the amplitude of the absorber motion, linear wave theory may be inaccurate.

Hydrodynamic modeling of the panel is outside of the scope for this work. Further reading about non-linear hydrodynamic models of OWSC-type device is available at [80, 81, 82].

3.4.2 Linearizing Mechanism

The rotational motion of the panel is transformed into linear motion by a slider-crank mechanism. This mechanism moves a drivetrain with a two-headed cylinder that delivers mechanical power from the panel to the hydraulic cylinders. The mechanism consists of an axial plane connected centrally to the panel, a connecting rod attached to the crank at its outer edge and a two-headed linear shaft sliding along guide bearings.

The drivetrain carries power according to its velocity v_D and the total force caused by the PTO cylinders on the drivetrain F_D. The crank head is connected to the panel and has the same rotational velocity ω_{crank} as the panel ω_{panel}.

For power we write [83]

$$\omega_{crank}(\tau_{crank} - \tau_{fric,crank}) = (F_D - F_{fric})v_D \tag{19}$$

where τ_{crank} is the torque caused by the slider crank on to the panel, and$\tau_{fric,crank}$ is the loss caused by crank friction.

The relationship between the crank rotational velocity ω_{crank} and drivetrain velocity v_D is

$$v_D = \omega_{crank}R(cos(\theta_{crank}) + \frac{R}{2L}cos(2\theta_{crank})) \tag{20}$$

where R is the distance from the crank central point to the connecting rod attachment point, in other words the radius of the crank, and L is the length of the connecting rod, and θ_{crank} is the angular displacement of the central crank mechanism.

For force continuity, combining Eq. (19) and Eq. (20) and rearranging yields

$$\tau_{crank} = (F_D - F_{fric})v_D\tau_{fric,crank} \tag{21}$$

The slider-crank mechanism introduces more losses in the power conversion chain, and due to the large instantaneous forces caused by the waves, has to be designed bulky and durable. The alternative to this kind of linearizing mechanism is to mount the cylinders directly on the panel, and account for the variable angle in some other way.

3.4.3 Hydraulic System

The closed loop hydraulic circuit consists of two parallel oil lines with distinct pressure levels, high pressure (HP) and low pressure (LP) lines. In contrast with open loop circuits, where the low pressure oil is at ambient pressure, both lines maintain a positive pressure relative to the ambient air pressure during operation. Closed loop systems can achieve higher total efficiencies, at the cost of a more complicated piping design[84].

Hydraulic cylinders convert mechanical translational energy into oil flow. The force caused by a hydraulic cylinder on its piston is related to the area of the piston in the cylinder A_p and the hydraulic fluid pressure in the cylinders $p_{cyl,A}$ and $p_{cyl,A}$.

$$F_D = A_p(\Delta p_{cyl}) - F_{fric,cyl} \tag{22}$$

The mechanical work the piston does pushing hydraulic oil out of the cylinder on the volumetric flow rate Q_{cyl} and oil pressure p_{cyl}. Flow rate depends on hydraulic piston surface area A_p and piston speed v_{cyl}. For the single cylinder

$$Q_{cyl} = A\ v_{cyl} P_{hydr} = Q_{cyl}\ p_{cyl} \tag{23}$$

Hydraulic check valves permit the flow of oil in one direction and prevent it in the opposite direction. The PTO hydraulic system includes four such valves, two per hydraulic cylinder. Their purpose is to rectify the cylinder oil flow. As only the flow to the high pressure line contributes to an increase in the energy level of the hydraulic system, and the low pressure line oil flowing into the cylinder at other part of the cycle does not remove energy from the system, we can write

$$Q_{check} = \begin{cases} Q_{cyl}, if\, p_{cyl} > p_{hp} \\ 0, otherwise \end{cases} \tag{24}$$

where p_{cyl} is the pressure inside the cylinder, and p_{hp}, the pressure in the high pressure hydraulic line. This means that the oil is always flowing from the cyliders to the high pressure line as the cylinder is contracting, and oil flows from the low pressure line into the cylinder as it is extruding.

One of the key advantages of hydraulic systems in high torque, low velocity applications, in comparison to pneumatic systems, is that the medium of energy transport is close to incompressible [5]. This means that the hydraulic system experiences only a very small amount of spring effect, and when the flow stops, pressures drop almost instantly throughout the system. In this application, this is undesirable, as rapid pressure changes in the hydraulic system translate to sudden spikes in energy production. Hydraulic accumulators used in this device are piston-type. They are cylinders containing an oil side and gas side, separated by a free-moving piston. As the piston has the same surface area on both sides, the pressure on both sides is the same. Increasing oil pressure causes a positive oil flow, and the piston to move towards the gas end, compressing the gas. As the oil pressure decreases, the gas expands, pushing the piston to the oil end, and causes negative oil flow. Hydraulic accumulators can achieve efficiencies up to 95%, with losses mainly occurring due to piston friction and thermic heating of the compressing gas.

3.4.4 Hydraulic Motors

Hydraulic motors convert hydraulic oil flow into rotational mechanical energy. In this way, they can be seen as the inverse of a hydraulic pump that generates oil flow from rotational energy. The designs can be divided into two broad categories, fixed and variable displacement motors. As the name suggests, the amount of oil required to spin the motor and the attached shaft for a single turn can be adjusted in the case of variable displacement. This allows for a wider range of oil flow values while still producing energy, although at lower efficiencies.[85]

A multitude of different variable-displacement hydraulic motor designs are available commercially, but they all follow the same basic relations between hydraulic oil flow and shaft rotation. Shaft torque τ_s is dependent on motor volumetric displacement D_m and pressure difference between high pressure and low pressure circuit $p_{HP} - p_{LP}$.

$$\tau_s = D_{cur}\delta p_p - \tau_{loss} = u_m D_{max}(p_{hp} - p_{lp}) \tag{25}$$

where u_m is the ratio between the current volumetric displacement D_{cur} and maximum volumetric displacement D_{max}. Mechanical losses caused by friction between the parts reduces the effective torque by τ_{loss}.

The oil flow through the motor is also dependent on the volumetric displacement D_{cur}, and rotational speed of the motor mechanism ω_m.

$$Q_m = D_{cur}\omega_m - Q_{loss} \tag{26}$$

with the hydraulic losses Q_{loss} caused by oil leaking through the fittings into the motor casing without interacting with the shaft.

Relationship between losses Q_{loss} and τ_{loss}, and the actual useful flow and torque are usually given as pressure- and volume-dependent co-efficiencies for hydraulic efficiency η_{hydr} and for mechanical efficiency η_{mech}.

Mechanical power at the motor shaft P_{mech} is equal to the rotational speed of the motor ω_m times the motor torque τ_s

$$P_{mech} = \omega_m \tau_s - Q_{loss}\delta p_p \tag{27}$$

The choice of motor type is limited by the maximum power levels handled by the various mechanisms. In wave energy applications variable displacement is very desirable, due to the large variations in power input and output. Variable displacement axial- and bent-axis hydraulic motors are common in industrial applications, and handle relatively high pressures [86].

High efficiencies at large areas of the operational range are usually not possible in traditional variable motor designs, and some compromises between motor maximum oil flow and total efficiency need to be made.

3.4.5 Electrical Generator

Producing electricity from rotations of a shaft requires a generator. As the device is to be installed underwater, where regular service is not feasible, the most interesting concepts [79] are an asynchronous induction generator, a doubly-fed induction generator, and a permanent magnet synchronous generator. For safety reasons, an asynchronous induction generator was chosen, as incorrect operation of permanent magnet or doubly-fed generators could lead to a situation where the hydraulic system is running without a grid connection, causing dangerous voltage levels to accumulate to the generator poles.

Asynchronous induction generators are rotating electrical machines that consist of two sets of rotating coils, the stator, that is stationary and fixed to the generator chassis, and the rotor. As the rotor moves about the stator, the changing magnetic field caused by the rotor coils induces a current on the stator coils. Stator coils are connected to the electrical grid. If the rotor is rotating at a lower frequency than the stator, the rotor will draw energy from the grid and spin, and vice versa.

Induction generators can be connected to the grid directly. In this case, as long as the grid has a stable frequency, the generator will be forced to spin at the same rate, in other words the generator is locked in to a static rotation speed. Another choice is to use power electronics that act as an artificial grid, allowing the generator to run at frequencies other than the grid frequency.

The torque caused by the electrical generator τ_e depends on the currents and magnetic fluxes of the stator i_s,λ_s and rotor i_r,λ_r [79]

$$\tau_e = \frac{3N_p}{4}(i_s\lambda_s - i_r\lambda_r) \tag{28}$$

where N_p is the number of poles in the generator.

The rotor speed ω_r depends on the difference between the electrical torque τ_e and the hydraulic torque τ_s

$$\omega_r = \frac{\tau_s - \tau_e}{J} \tag{29}$$

where J is the rotor moment of inertia.

3.4.6 Power Conditioning

A variable speed power converter is used to alter the operating frequency of the asynchronous electrical generator. As the generator is directly coupled to the hydraulic motors, by adjusting the speed the hydraulic motors can be allowed to operate in a more optimal efficiency area.

Such devices consist of a direct current circuit surrounded by two power electronics blocks capable of transforming alternating current to direct current. These AC-DC-AC devices do not convert energy into other forms, and they act as an additional control parameter source, that can be modeled as an energy loss.

The power generated needs to be transferred from the sea closer to the electrical infrastructure located on the dry land with a subsea cable. A transformer can be used to increase the voltage levels in the subsea cable in order to minimize the current in the cable while maintaining the same power transfer capacity. Another transformer would be between the shore substation and the local medium-voltage or high voltage grid.

3.4.7 Grid

Electrical grid, as meant here, is an abstract concept that represents the complex network of interconnected electrical carriers, generators, consumers and transformers. Definition of the borderline between the PTO and the electrical, the point-of-connection by which the generated electrical tariff is paid for, depends on the agreement between the network operator and the WEC owner.

Dropping out everything else from the power conversion chain but the electrical grid is meaningless, as that would leave us with nothing but a wall socket. However, turning the test setup around, using actual hardware for electrical power generation, and then emulating the electrical grid gets us back on the track for meaningful trials. Not all possible installation locations for wave energy devices have access to a strong electrical grid, and testing the device responses to an unstable local electrical network is a necessary step in determining the generator functionality [10].

The electrical grid could be 'emulated' by connecting the device to the national electrical grid, and achieving compliance with its grid code. The local grid at the test facility should be sufficiently stable to not get interrupted by the electrical output of the PTO. An additional device used to generate artificial grid faults could then be inserted between the grid and the power take-off.

3.5 Test Bench Target

As wet-testing a full scale PTO in a controlled tank environment has been deemed impractical, and testing it in actual ocean waters is very costly, alternative methods have to be devised, and some parts of the WEC have to be emulated. Emulation here means to construct a device that can produce powers sufficient to match the power projected to be caused by the actual ocean waves. The device used to emulate the movements caused by the waves should be sufficiently powerful to emulate the most relevant sea states.

In general, the earlier in the power conversion chain the emulation point is, the more of the PTO functionality can be tested. On the other hand, more equipment necessarily requires more financial investment, more instantaneous power and a larger facility.

Additionally, there is a trade-off between force and velocity to consider. Given a certain power, classical mechanics equation $P = F * v$ shows that the greater output force we require from the emulating device, the less velocity it can produce. This means that identifying the maximum force allowable for the PTO, and scaling the power to produce sufficient velocity is a major design challenge to consider.

Presented here are some emulation points considered for the WaveRoller PTO test bench:

Moving the entire converter with a mechanical actuator Removing blocks from Fig 15 starting from the left, the first choice is to remove the wave interaction but retain the absorbing body, using other mechanical means to emulate the input force F_{ext}.

The Irish wave energy company Wavebob has adopted this strategy, and outline a hardware-in-the-loop simulation test rig for their buoy-type WEC [87]. They have installed the complete WEC with absorbing body and PTO, but are using a hydraulic system to move the absorber. They conclude that the test rig can successfully emulate the wave forces. They note this to be a small scale experiment, not disclosing scale factor.

This approach has the advantage of including the entire WEC, allowing complete systems test before deployment. However, the law of increasing power capture with increasing absorber surface area dictates that the absorbing body ought to be large, as is the case with Waveroller and other OWSC designs. As the panel structure is designed to be buoyant, moving it around at dry land requires considerably more force compared to its natural habitat in the ocean.

Machines allowing for such forces are not rare, but the force-velocity trade-off here would mean that panel rotational velocities achievable would be very small in magnitude.

This kind of testing also requires to construct the entire WEC and assemble it, meaning large capital investment. Committing a full WEC for a long-term PTO product development process was seen as financially unfeasible, but this method of testing could be useful in post-assembly, pre-installation system verification tests done at a dockyard.

Emulating rotational movement of the panel Eliminating the need for a water tank and the panel structure requires us to move forward in the power conversion chain. Using a rotating machine attached to the drivetrain, and using it to simulate the torque and rotation caused by the panel would allow us to test the PTO in its entirety. This would be a very interesting test arrangement, as the power transmission mechanism in its entirety could be tested.

Rotating wave simulator machines that could produce sufficient torques and speeds to accurately simulate the panel are necessarily very large. Compared to typical rotating machinery, the ocean wave frequency of about 0.1 Hz is extremely low, and the torque required is comparatively high. Machines designed for this low rotational speed and very high torque do exist, for example the tidal turbine test site at Northumberland, UK [88]. The problematic part is the requirement for changing directions mid-rotation.

Additionally, the drivetrain is a relatively simple mechanism, but expensive to manufacture and move around. Weighting the costs of commissioning a rotational test bench, and balancing them against the assessed design risks, a financially viable technical solution was not found. A rotating machine of this size would also require extensive protective measurements, increasing the size of the test bench greatly.

Linear movement of the drivetrain cylinder The next possible step is to use a translational rod to simulate the movements of the two-headed slider-crank mechanism known as drivetrain. This linear movement is used to cause an hydraulic power flow out of hydraulic cylinders.

System producing the translational motion is required to achieve high force levels at low velocities. For the power transmission in WEC PTOs, hydraulic systems, rack-and-pinion mechanisms and linear electrical systems. For a hydraulic PTO, the choice of a hydraulic wave simulator is easy, as maintaining two hydraulic systems enables synergy in terms of maintenance, spare parts and personnel competence required in contrast with two different linear movement techniques.

Using an open loop hydraulic system with pressure accumulators as an intermediate energy storage could improve the peak power output of the hydraulic cylinder, and thus allow for more extreme wave conditions to be simulated. The choice to use a closed hydraulic loop was due to the higher sustained power levels.

Emulate hydraulic oil flow with pumps Leaving the hydraulic cylinders out of the equation would simplify the hydraulics required. Emulating the oil flow that would be caused by the hydraulic cylinders with hydraulic pumps would mean that only one hydraulic circuit would need to be constructed. Most of the subsystems would still be able to be tested, including the hydraulic accumulator system.

Hydraulic cylinders are partly custom-made, and were identified as a major source of design uncertainty. To mitigate this risk, the idea of leaving the hydraulic cylinders out of the test bench was dismissed. This approach has been used by some test projects with success, however [89].

Unit testing the generator, power electronics, transformers or other parts Eschewing the hydraulic system completely, and emulating hydraulic motors with some other rotational energy source would have tested only the electrical equipment of the PTO. This sort of a unit testing setup would be necessary if the generator was a novel design, specifically made for purpose part. As this is not the case, and the generator is a well-known design with proven performance, this type of test was dismissed as unnecessary.

For the other parts in the electrical circuit, including the frequency converter and grid transformer, the story is similar.

It is notably difficult to ensure grid compatibility without an electrical infrastructure test rig [90], and these machines should be included in the test system.

Emulating the grid Grid connection point at the testing facility is connected to a very stable local 20 kV distribution network, and is virtually unaffected by the operation of the test machines. To test the system's response to adverse electrical grid conditions, as required by the grid codes of most electrical networks before generators can be connected, a grid interface instrument capable of emulating power outages and other possible electrical issues was constructed. Ready-made devices for this type of testing are available, and are widely used in renewable energy industry to ensure grid compliance.

This is partially unrelated to the PTO testing, as the main focus of the testing facility was the hydraulic systems and not the electrical ones.

In the end, the choice to emulate the linear motions of the slider-crank drivetrain was made as it gave the company the possibility to test the entire hydraulic system of the PTO. The drivetrain mechanism and the rotating machine to turn it were deemed too costly and too unsafe to operate for the benefit they would have offered. Hydraulic pumps connected to a double-acting, double rod, balanced hydraulic cylinder was the choice of machine to deliver that linear motion.

Additionally, the test bench was required to be safe and simple to operate. The product development process would likely necessitate changes on the testing bench equipment, and modifying a hydraulic system is fairly simple compared to a large rotating machine. The aim of the test bench was to test the hydraulic and electrical characteristics of the system rather than simple mechanics.

4 Similar Devices

In order to evaluate what others have done with wave energy converter test bench setups the most prominent examples from the industry are explored. There have been decades worth of many types of small scale experimental rigs for wave energy converters documented in the academia. As their role has been to act as a proof of concept or student training platform, rather than serious attempts to represent full scale power take-off dynamics in controlled environments, they are not considered relevant. This is likely a matter of cost, as large and powerful hardware needed to simulate power levels of WECs is costly.

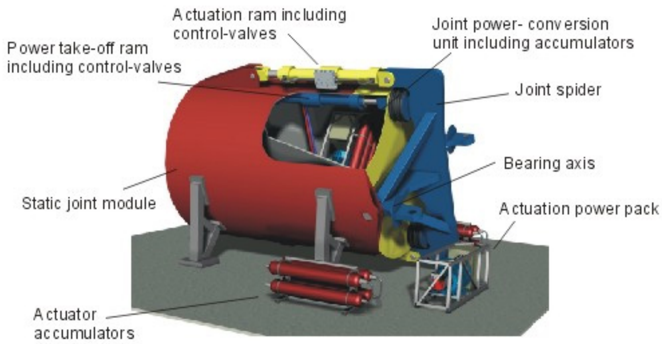

Figure 17: Picture of a single joint of the Pelamis device PTO module and its testing system

4.1 Pelamis Wave Energy

Pelamis Wave Energy constructed a full-scale PTO test rig (Fig. 17) for their floating, rotational WEC with hydraulic power-take off [91]. Their WEC concept consists of multiple identical segments interconnected, each equipped with a PTO module. Their test setup included single such PTO. The simulating hydraulic machinery is rated at 250 kW sustained output power. To emulate the movements that would be caused by the relative motions and forces of the WEC segments on the PTO. As with AW-Energy test facility, the test bench and PTO hydraulics are completely separated, and controlled individually. This setup would simulate the movement of the floating body segments, and the rest of the PTO modules.

Their claimed goal was to measure the overall efficiency of the PTO, and to verify their simulation assumptions about their simulational models of the PTO. Also note that they used identical components planned to be used on the marine device. Conclusion drawn is that the simulation model of the PTO, 1:7 scale tank test and the test rig were in agreement, and they claim total a conversion efficiency of 80%.

A non-peer reviewed engineering document [92] written about the facility reveals more details about the test rig. The primary goal of the test rig was to study the overall feasibility and functionality of the PTO module, to provide endurance test results to increase confidence in the reliability of the device and to give the system developers hands-on experience working with the actual full-scale components that would be later used to construct the marine device. The test rig did not include a possibility of testing stochastic sea states, nor did it include any sort of simulation for the primary mover, and relied on linear back-and-forth stress test suites as the input data.

The conclusion of the test was that the PTO concept was indeed workable, and that the cost and effort spent in full-scale testing were very valuable for the project, resulting in number of key improvements to the design and giving opportunity to assess the quality of the parts provided by prospective suppliers and partners.

Their test campaing was fairly short, only three months from commissioning to decomissioning.

4.2 Wave Star

Wave Star A/S and Institute of Energy Technology in Aalborg University have built a testing bench for the PTO of their their multiple-absorber, rigidly sea bottom mounted wave energy converter (discussed in [93]). The device consists of multiple (the dissertation quotes 20) independently moving arms connected to a floating point absorber. The arm is mounted on a non-floating, rigidly bottom mounted platform, that houses the PTO units. Each arm has an independent hydraulic PTO unit that hinders the movement of the arm and the float, and pumps oil through a hydraulic motor to generate electricity. To test this PTO concept, called the Discrete Displacement Cylinder (DDC), they have constructed a conceptually very similar test bench to the facility in Järvenpää. The device used to emulate the movement caused by the waves is a hydraulic cylinder. The stated goal of the test bench was to test the force control system of the DDC PTO. The DDC is used to approximate a causal reactive control algorithm used to control the force caused by the PTO to the absorber. The force controller itself is necessary for the PTO to increase the power capture greatly, as discussed in chapter 2. The challenge stated by the author is to simulate the very large mass momential inertia of the absorber-arm system with a relatively lightweight hydraulic piston.

The cylinder is driven by two different-sized hydraulic pump units (Fig 18) with a total input power of 350 kW in an open loop configuration. The wave simulation cylinder has a stroke of 3 meters and a rated maximum force of 840 kN. The wave simulation cylinder is controlled with a 4/3 way proportionally controlled hydraulic valve, where operating the valve diverts oil flow from pump units to either cylinder chamber, forcing it to move. The wave cylinder is coupled to the PTO via a force sensor that is used as the primary feedback for the wave simulation cylinder control loop. Taking the counter force caused by the PTO into account allows for the wave simulation controller to more closely simulate the real-world behavior of the WEC. The control system includes an on-line hydrodynamical simulation of the floating absorber dynamics, and allows for arbitrary wave height as the input signal(Fig. 19). The absorber is modeled with a linear first-order model that takes into account the internal potential and kinetic energy storage of the float. The absorber model

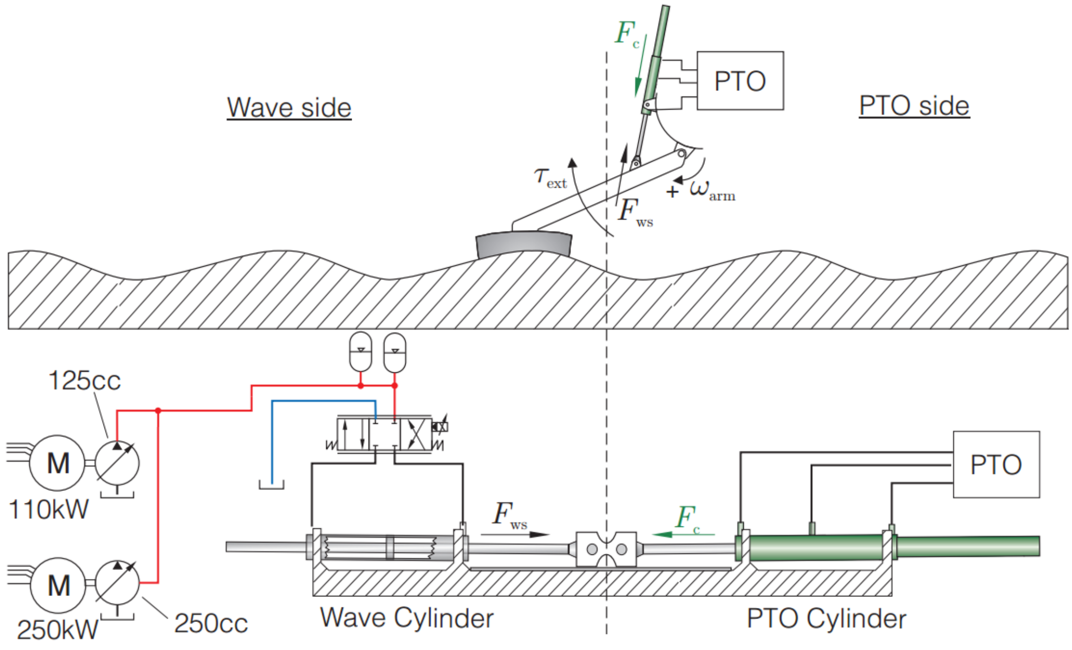

Figure 18: Conceptual drawing showing the principal and hydraulic design of the test Wavestar PTO test bench. [10]

outputs the rotational speed of the absorber arm ω_{arm} and the arm's current position θ_{arm}. Very similar to AW-Energy's test setup, this rotational motion needs to be mapped to linear motion. This kinematic model outputs the simulated speed $v_{c,ref}$ and position $x_{c,ref}$ of the piston connecting the absorber arm and the PTO cylinder. These references are used as inputs for the wave simulation hydraulic system controller. The complex control system is a mix of empirically tuned feed-forward and feedback loops, including an dynamic model of the spool dynamics and a flow feedback component.

The conclusion drawn by the author is that this type test setup is viable, and that the advanced control algorithm is able to emulate the dynamics of the wave absorber. The control system implemented in this work is very interesting, and the conclusions drawn seem very reasonable.

4.3 WavePOD

Aquamarine Power Ltd. and Institute for Fluid Power Drives and Controls (IFAS) at RWTH Aachen University constructed a 1:10 scale test rig for a wave energy PTO dubbed the WavePOD [94]. Aquamarine power has been developing an OWSC type near shore, bottom hinged WEC similar to WaveRoller. Their original concept was to pump water to the shore from the device offshore via a subsea pipeline [95]. The electricity generator was done entirely onshore. Later on, Aquamarine Power decided to diversify their technological options, and changed gears to develop an universal power take-off module for WECs [96] that would be placed entirely into

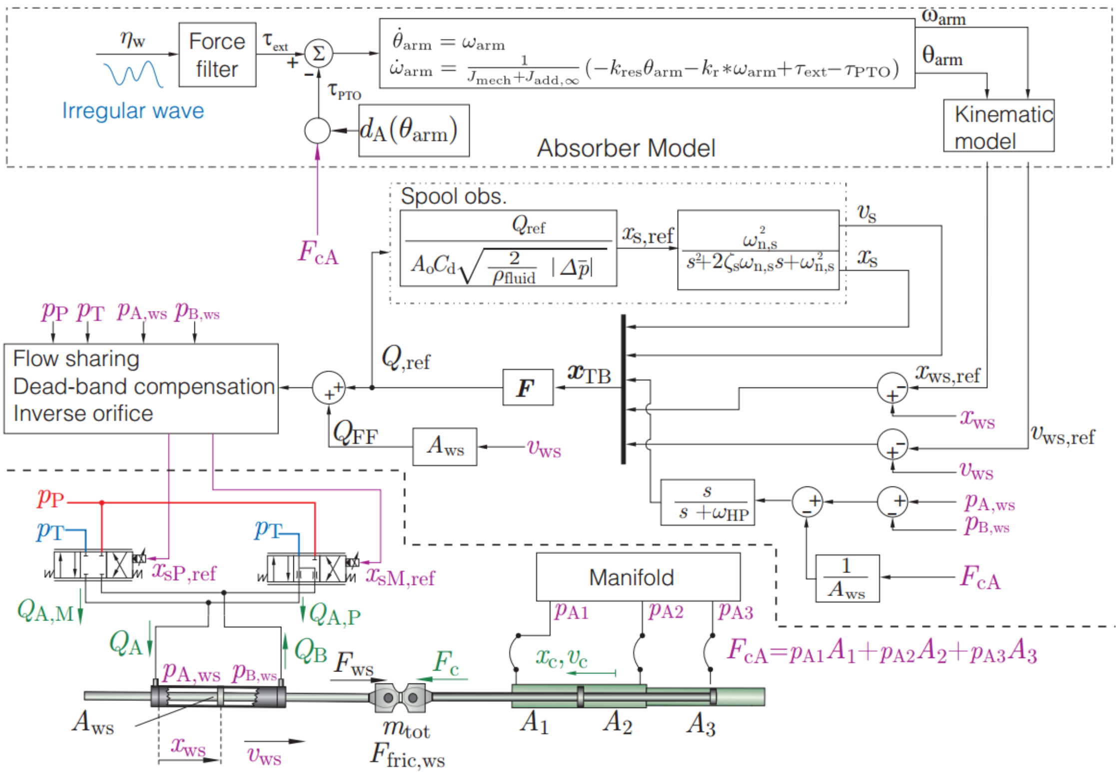

Figure 19: Detailed Wavestar test bench control algorithm diagram. The controller is a model predictive control system, as it has a detailed model of the system dynamics used to calculate the reference. The reference is then corrected by actual values of the system parameters [93]

the ocean. WavePOD is developed in cooperation with the hydraulic industry giant Bosch Rexroth and another wave energy company, Carnegie.

The test bench at Aachen University is a closed loop hydraulic test bench rated at 80 kW continuous power [97], and with the aid of accumulators, 1 MW instantaneous peak power. The test bench cylinder is moving a centrally mounted level arm, that in turn actuates PTO hydraulics, see Fig. 20. The control algorithm for the test bench contains a feedback from the PTO module into a simple panel equation of motion. The simulation produces the reference signal, compared to the actual lever arm angle, and used to control a servo valve that drives the wave simulator cylinder oil flow. Mechanism of the PTO itself is not presented.

The intended aims of bench testing the PTO are to be a proof of concept and providing feedback for the design of the system, single component and system integration validation, and to aid PTO fault situation simulation and planning for corrective action. The tests are intended to be long term, gradual evolutions of the machine. Conclusions that they draw so far are that the control they have implemented can be reached with only small errors, and that continued testing is required before technological readiness can be achieved.

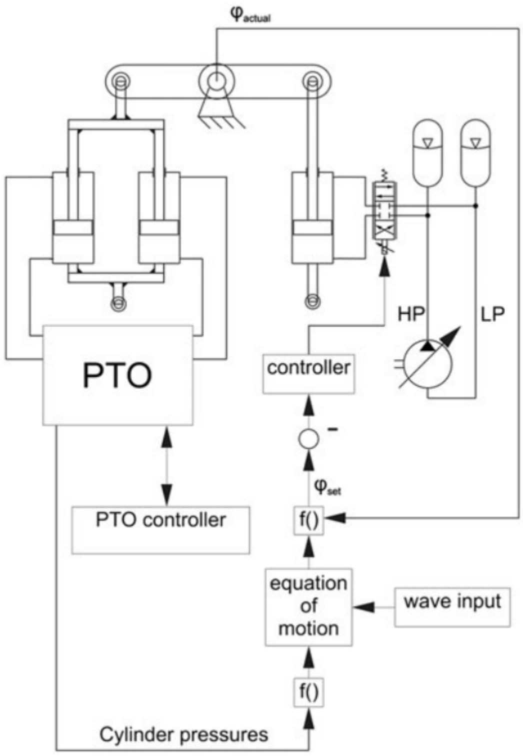

Figure 20: Combined hydraulic and control drawing of the WavePOD PTO and test bench. The PTO force is fed back to the hydrodynamic model used for control. [94]

4.4 BioWave

An Australian company called BioPower Systems has designed a OWSC device called BioWave, and a detachable PTO module to go with it called O-Drive [98]. They have revealed a limited amount of information about their power generation concepts, but they have tested their PTO in a test bench from 2009 until at least 2014, suggesting long-term, iterative testing and design process. They have constructed a 250 kW rated power PTO system, and they claim they are testing it in a factory environment in full scale[99].

4.5 Conclusion

Other wave energy companies that have reached the product development stage of preparing a full scale marine device for deployment have recognized the value in having a test bench for the PTO module. Common for all discussed test benches is the stated goal of verifying the design concepts, and assessing the viability of the system.

WavePOD and Wave star PTO test rigs include a hydrodynamic model with the PTO force fed back into the model. This approach allows precise testing of the force control method effectiveness and how it affects the power capture.

Following the classification established in the previous chapter, Wave Star has adopted the same approach as AW-Energy, using a hydraulic cylinder to emulate the movement of the linear translational part of the WEC power chain, and model the absorber hydrodynamics and the kinematics of the linearizing mechanism. The WavePOD test bench has included the mechanical lever arm coupling mechanism to the test bench, and is using a hydraulic cylinder to move the leverage arm. In this sense, their test bench contains more actual machinery and relies less on simulation accuracy. The Pelamis test bench simulation point is more difficult to place, as they have not attempted to simulate the actual motion of the absorber, and instead opted for generated sinusoidal test input.

Operators of other test benches note that long term testing of the PTO is required. With gradual optimizations and improvements that come as the understanding of the PTO dynamics increase, the testing campaigns can offer direct improvements to the PTO design.

5 Järvenpää Test Facility

After the operational experiences from the previous prototype device, the overall feasibility of the concept was reaffirmed, but a number of improvements were seen necessary before the product could be launched commercially. One of the redesigned parts of the system was the power take-off mechanism. The commissioning of the power take-off mechanism in the previous device was not as simple as thought, and PTO testing was identified as a high importance task. The new PTO design was to be verified and tested before it would be implemented.

As other wave energy design teams had done before, it was decided that a dedicated testing facility for testing the mechanical and electrical systems on a full scale PTO was needed. Hydraulic cylinder was chosen as the prime mover of the wave simulator for the reasons discussed in Chapter 3. The wave generator device was designed and built mostly during 2014. After the initial PTO design was finalised, the PTO system was constructed around the wave simulator. The test device was initially commissioned in June 2015.

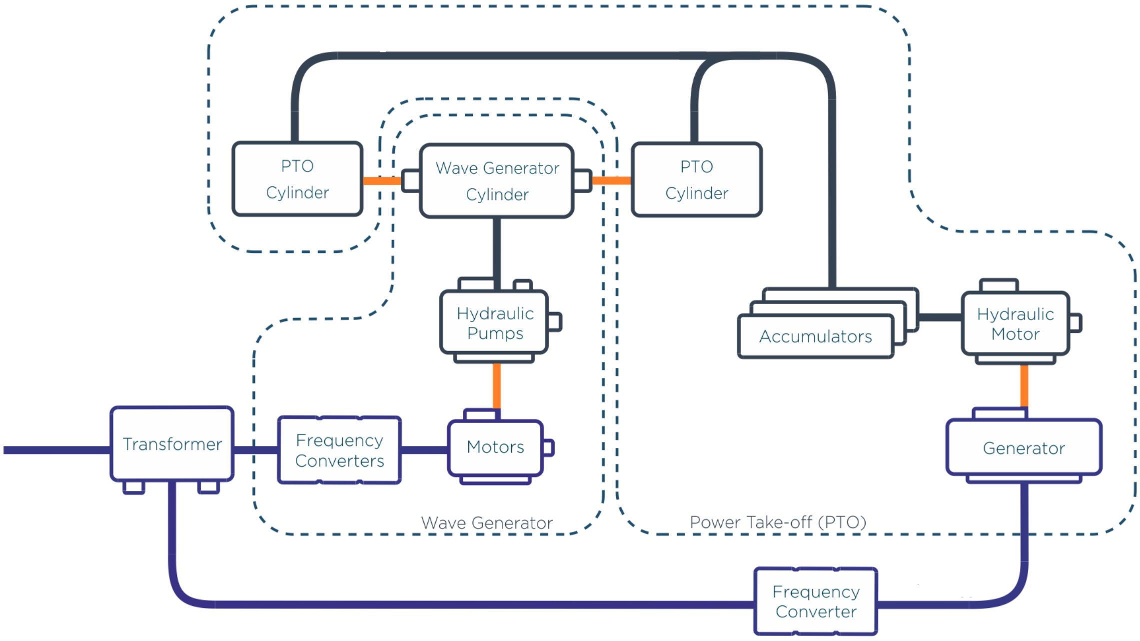

Figure 21: A system-level illustration of the main components and power types. Blue lines represent electrical connections, black lines are hydraulic connections and orange lines are mechanical connections.

5.1 Test Bench Goals

The test facility was comissioned to test a novel power take-off module for the WaveRoller WEC. Using the same components, measurements and automation systems for the test bench as for the marine device allows us to assess the viability

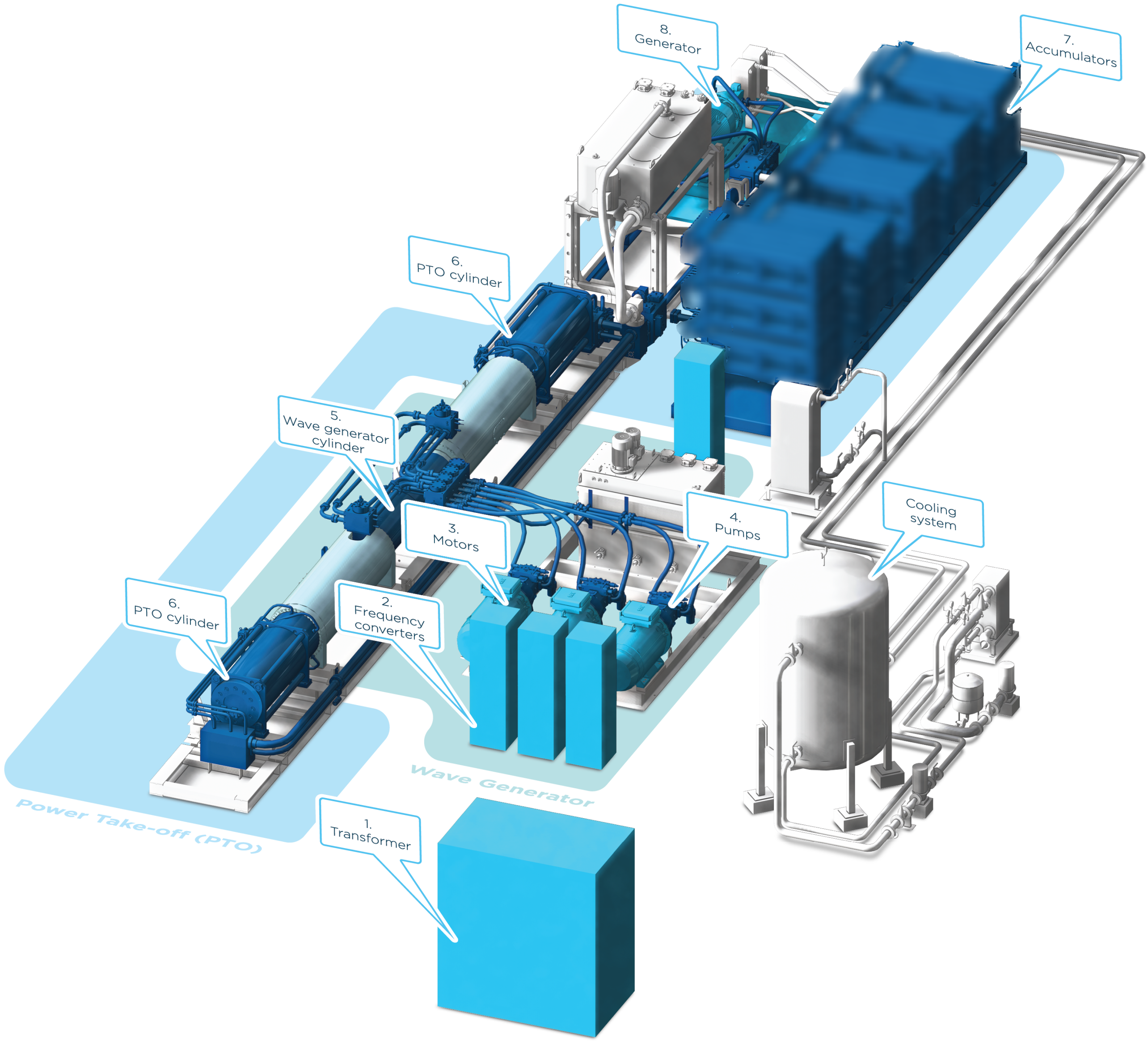

Figure 22: 3D rendering of the testing facility components. Division into separate hydraulic systems with individual oil reservoirs.

of the design beforehand. Before the comissioning and designing of the test plant, some key results to gather were identified:

Verify the design assumptions made about the hydraulic system. The PTO hydraulic system consists mostly of off-the-shelf components. For some parts, where the size or shape is unusual, like the hydraulic cylinder units, the parts need to be custom-made. Ensuring the compatibility and fitness of the components before installing them in a marine environment, where servicing or replacing them would be very costly, is a major advantage of a full scale test rig.

Confirming power smoothing dynamics. The hydraulic accumulator system acting as an intermediate energy storage is an uncommon use for hydraulic accumulators. Typically, hydraulic accumulators would be used as shorter term (less than one second in duration) capacitors to smoothen pressure shocks inside hydraulic circuits, or as very long term storage of static pressures used for ensuring the safe operation of certain devices. As wave periods found in oceans are in the range of 5 to 15 seconds, the accumulators need to store energy during the energetic wave movement and release it during the zero-crossing period of the waves. This type of usage for the accumulators is to be tested.

Measuring power conversion system efficiencies. Having detailed measurements of the PTO system parameters, and the exact input power measurement from the wave generator, allows for a detailed analysis of the power conversion chain. Calculating the power at each point of the power conversion chain and comparing it to modeled predictions can reveal inefficient design choices inside the system.

Force control testing and tuning. A novel hydraulic system was designed to control the force produced by the PTO. A properly implemented force control algorithm is known to increase the power capture potential of the WEC by significant amount. The hydraulic system was implemented for the test facility PTO. The force control method or the algorithm used for it are not discussed in this thesis due to intellectual property concerns. Testing the feasibility and operation of the force control, and fine tuning the control algorithm for maximal power capture in the Peniche wave climate were planned.

Provide a platform to develop and test automation systems. A preliminary design and implementation of the automation system to control the PTO automation system was planned during the design phase of the facility. The commissioning and fine tuning of the automation system, as well as testing systems integration, before moving to the marine device, was a major goal.

Establishing a Supply Chain Building a full-scale PTO test device instead of a smaller scale model has the advantage of enabling the usage of the exact same components as the commercial product is to consist of. The device is to be built almost entirely out of established, off-the-shelf parts. To decrease costs, each part or subsystem should be independently evaluated in terms of requirements, market offerings and price. Going through the actual procurement process during test bench construction allows to evaluate the offerings of potential suppliers, the responsiveness and reliability of their delivery processes, and the amount of post-sale technical support and consulting available. Hydraulic, electrical and automation products mostly follow standards, but the interoperability between systems from different suppliers still needs to be established.

Manufacturing Process Design Procuring the necessary parts to assemble the machine is only a part of the manufacturing process. When designing a new product that has no clear comparison point in the industry, the practicalities of the assembly process need to be established in order to assure safe and fault-free operation. The procedures for testing and ensuring operationality also need to be established. An incorrect installation of the hydraulic parts could result in an oil leak during operation. The hydraulic system is confined within a hermetically sealed steel steel structure, and the possible oil leak would not come into contact with sea water or pollute the ocean. Loss of oil will lead to a halt in energy production, and due to the marine environment it could cause a very costly unplanned maintenance. Assembling the test bench also gives the personnel involved the ability to familiarize themselves with the equipment and installation procedures.

Preparation for Commerzialisation Pricing a commercial wave energy device requires accurate knowledge of the costs, risks and challenges involved in manufacturing, operation and maintenance. Potential customers would require feasible estimations of total lifetime costs compared to energy production, as there is no actual operational experience from wave energy industry to rely on. Various methods at estimating actual operational costs can be developed, but their accuracy remains questionable. Operations at the test facility give a way to improve the assumptions used in financial calculations.

Standards Compilance Permissions to install wave energy devices at the shoreline vary greatly between jurisdictions, but generally, some sort of assurance about the safety and functionality is required. Preliminary standards specifically designed for wave energy do exist, but have yet to reach widespread adoption. Testing against these standards, or against some more generic offshore or renewable energy standards, is a way to demonstrate technological readiness and to communicate it to the permission granting authorities. As doing standard compliance testing in the marine environment would be very difficult and costly, the testing facility is to be used for this kind of activity wherever feasible.

Act as a technology showroom. The entire wave energy industry has an image problem. As no successful commercial wave energy project has ever been launched even after decades of research, the skepticism of potential customers or technology partners is understandable. Being able to demonstrate the structure and operation of a working, full scale machine in an indoors, easily accessible environment was seen as an important public relations asset.

5.2 Automation System

The completed test facility consists of three parts, the wave simulator hydraulic system, the power take-off, and the cooling system (see Fig. 21, 22). The control systems for the wave simulator and PTO are kept almost completely separate. The only direct communication between the systems is an emergency stop signal, needed for machine safety reasons as a way to force all movement in the facility to halt in case of an emergency.

The test bench side of the facility is controlled by a programmable logic controller (PLC). In addition to controlling the variable frequency drives, electric motors and hydraulic pumps used to actuate the main cylinder, it handles a variety of different industrial automation tasks.

The analog to digital conversion of the measurements. The test bench hydraulic system and its cooling system contain about a hundred different electronic instruments used to monitor the system parameters to maintain safe operational limits and to monitor the condition of the equipment. Analog-to-digital conversions of the measurements is handled centrally at the control cabinet. A fieldbus interface is used to communicate with the variable frequency drives, both the smaller cooling pump drives and the large main electric motor drives.

The closed loop water cooling circuit. The hydraulic system is cooled by oil-water heat exchangers. Both the hydraulic systems are connected to a common cooling system that exchanges water to and from a 10-cubic-meter water reservoir. The water in the intermediate water circuit is cooled with heat exchangers connected to a freezing-resistant glycol-water mixture pumped to out of the factory floor on to the roof, where it is cooled with air fans and heat pipes. The cooling system is entirely controlled by the test bench PLC, via simple PID controllers for each of the cooling loops. By modifying the set point for the intermediate water tank, different ocean water temperatures can be simulated. Precise cooling water temperature and flow measurements for each cooling line allows to calculate the total cooling power required for each line.

Security features. Due to the high power and force levels present in the system, and the large amount of energy stored in the gas-charged hydraulic accumulators, personnel cannot be present in the testing area during operation. All operations are performed and monitored from an attached control room. To prevent accidental access to the area, electrical locks are engaged on all doors leading to the test area. To ensure safe operation, the system is automatically halted if abnormal measurements are recorded from the field instruments.

5.2.1 SCADA system

To monitor and control the system safely, the operations are performed from a separate control room. To visulize the measurements from the system, and to issue commands to the automation Programmable Logic Controller (PLC), a computer software commonly called Supervisory Control And Data Acquisition (SCADA) has been developed. The connection from the PLC controller to the PC environment is done using a proprietary data driver provided by the PLC vendor Siemens. The SCADA software itself, illustrated in Fig. 23 is designed with a toolset from Schneider Electric called InduSoft.

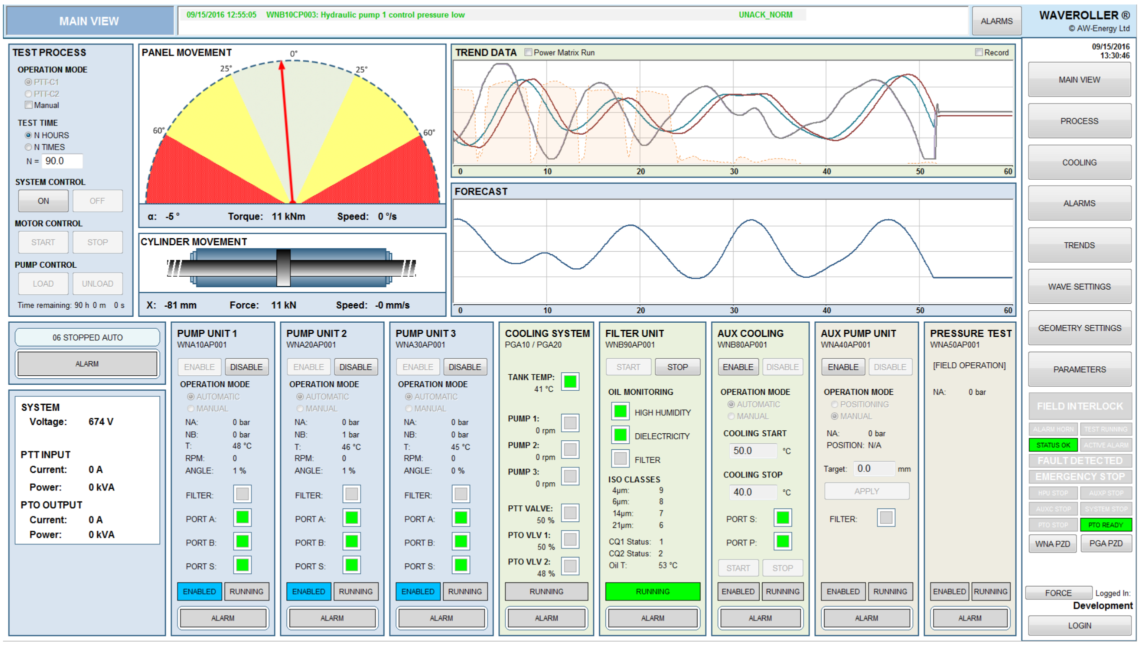

Figure 23: Screenshot from the SCADA home screen.

Typical functions included in SCADA systems are alarm handling, process control, process parameter monitoring and visualization, and various trend displays. All of these are implemented in the SCADA program for the wave simulator. As the wave simulator is a testing tool for internal use and not a part of the WEC product, the visual fidelity and user experience design have not been a priority.

The SCADA system allows to change the parameters used for the drivetrain calculation, and to change the 30 minute input data. If desired, a sine wave time series can also be used as the input data.

The testing area and the machine enclosures are monitored with a recording camera system. The camera feeds are recorded, both for reviewing security footage in case of a breach, and for reviewing machine enclosure footage in case of a breakdown or an oil leak.

5.3 Wave Simulator Hydraulic System

The purpose of the wave simulator is to simulate the forces and movements caused by the panel and the drivetrain as closely as possible. This enables us to test and fine tune the PTO module as closely as possible on dry land. To achieve this, the test rig must be able to move the PTO cylinders in a manner that replicates the simulated movement caused by the panel and the drivetrain of the WEC. A hydrostatic transmission system was seen as the most practical solution for generating very high forces in linear motion. Unlike mechanical constructions, hydrostatic transmission is capable of providing constant forces and high torques at low speeds [100].

The primary movers for the wave simulator are 550 kW rated power asynchronous

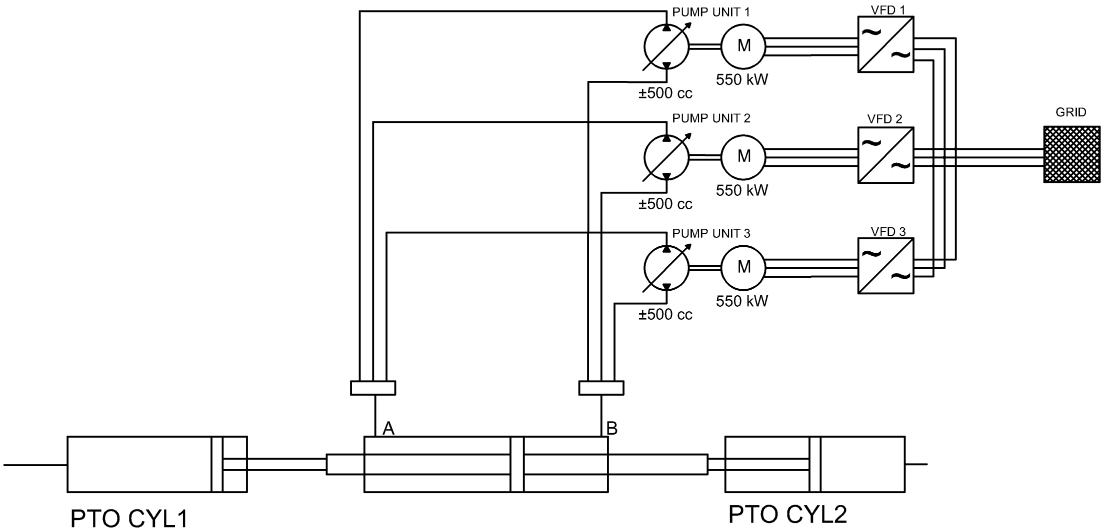

Figure 24: Simplified wave simulator hydraulic layout.

electrical motors. These motors are driven by variable frequency drives to enable easy startup and the potential to vary rotation speed.

Hydraulic power is generated by three variable displacement swashplate axial piston pump units. Hydraulic pumps, in general, convert mechanical rotational energy into hydraulic energy. The hydraulic pumps are installed in a closed circuit configuration. Closed circuit means that the oil returning from the actuator is fed directly into the inflow port of the pump. This is in contrast an with open loop configuration, where the oil is drawn from a reservoir and the returning oil is simply released back to the tank. Open loop hydrostatic transmissions are simpler to construct, as there is only one pressurized line, as the return oil line is at ambient pressure. Closed loop systems have two pressurized lines, and allow for a more precise control, and a higher total efficiency [100].

Variable displacement means that the amount of oil displaced by the pump per revolution is not constant, but can be controlled. The hydraulic pumps used are axial piston pumps that can have their displacement per rotation from idle (no flow in either direction) to 500 cubic centimeters in either direction. Axial piston pumps contain a spinning barrel, connected to the shaft powering the pump. Connected to the barrel are a number of hydraulic pistons that spin with the barrel, periodically passing over the inlet and outlet ports of the pump. THe pistons are connected to a non-rotating swashplate with ball-and-socket joints. The outflow of the hydraulic pump is varied by varying the angle of the swashplate θ_{sw}. At neutral position, the pistons pass over inflow and outflow ports without contracting or retracting, and thus causing no oil flow. Moving the swashplate position in either direction causes the pistons to move. As the piston passes over the inlet port, it retracts and fluid is drawn into the piston chamber. When the piston passes over the outlet port, it is forced to advance into the barrel and fluid is pushed out of the outlet port.

Flow of each hydraulic motor is controlled by electrical valves. The amount of oil pumped by the pistons per rotation, or the pump's geometric displacement V_g, or the volume of the pump, depends only on the swashplate position according to

$$V_g = V_{g,max} \frac{\theta_{sw}}{\theta_{sw,max}} \eta_v \tag{30}$$

Where $V_{g,max}$ is the maximum geometric displacement of the pump, θ_{sw} and $\theta_{sw,max}$ are the current and maximum angle of the swashplate, and η_v is the volumetric efficiency of the pump. The swashplate angle is expressed as a percentage of the maximum angle. The swashplate is able to move an equal amount in either direction from the neutral position of 0 %. At maximum positive angle, or 100 % reference, the maximum amount of oil is pumped from port A to port B. At -100 % reference, same amount of oil flows from port B to A. In other words, $Q_A = -Q_B$. Volumetric efficiency η_v represents the ratio of oil that is pushed to the outflow port to the oil that leaks into the casing of the pump. η_v is not a single constant for a given pump, and in fact varies greatly depending on the swashplate angle, the pressure difference, and the rotation speed of the pump

Hydraulic oil flow Q caused by the pumps can be calculated by

$$Q = V_g \omega_{shaft} - Q_{leak} \tag{31}$$

where ω_{shaft} is the angular velocity of the hydraulic pump's shaft, and Q_{leak} is the oil flow that leaks to the casing of the pump instead of flowing into the output port. The amount of oil leaking can be calculated from [100]

$$Q_{leak} = V_{g,max} \omega_{shaft} (1 - \eta_v) * p_{p,diff} \tag{32}$$

where $p_{p,diff}$ is the pressure difference across the pump ports A and B, given by $|p_{p,A} - p_{p,B}|$.

Instead of attempting to directly adjust the swashplate angle with electrical actuators, the swashplate is positioned with an auxiliary hydraulic cylinder. A double-ended piston is attached to the swashplate, as seen in Fig 25. Both chambers are connected to a four-port, three-position hydraulic valve (4/3 way valve). The valve is fed a control pressure via a smaller coaxial pump in an open circuit system. Adjusting the electrical current going to the solenoids of the valve, labeled a and b, the control pressure is directed to the cylinder chambers. As the piston moves, the internal springs and oil pressure at each chamber reach an equilibrium, and the piston will be held stationary. Changing the solenoid currents causes pressure to get released, and the swashplate angle to change.

The angle control algorithm of the swashplate for each pump is controlled with a cascade controller, illustrated in Fig 25. The primary input is the reference angle θ_{ref}. To prevent oscillations in case of non-continuous reference signal, the reference is conditioned with a ramp function that restricts the maximum change rate of the reference to be 100 % in 30 milliseconds. The measured swashplate angle θ_{act} is used as the feedback, and the difference is fed into a PID controller. The PID output is used as a current reference for the current controllers for the solenoid feed current.

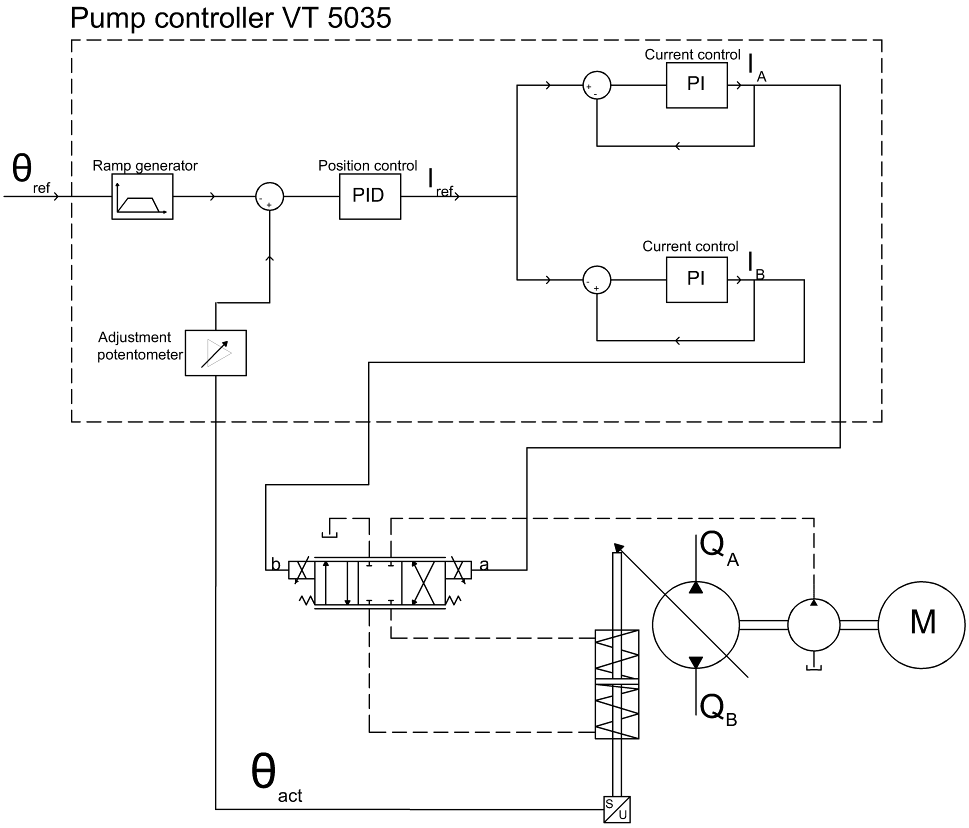

Figure 25: Control system of individual hydraulic pump units. Input for the pump controller is θ_{ref}. Hydraulic pump output is the oil flow $Q_A = -Q_B$.

The B-controller reference is the inverse of the A-controller reference, as the aim is to pull the valve spool equally. The output current is measured, and the difference is fed back into PI controllers.

The oil flow from all three pumps is congregated at a manifold block. The total flow through the block is preserved, and the oil flow is approximately equal for all three pump lines, so that

$$Q_{cyl} = Q_1 + Q_2 + Q_3 \tag{33}$$

Where Q_{cyl} is the flow going to and from the cylinder chambers, and Q_1, Q_2 and Q_3 the individual pump oil flows. The equation holds in both flow directions, and for both hydraulic pump ports A and B.

The double-rod hydraulic cylinder is the part of the system interacting with the power take-off unit. The oil flow into the cylinder forces the piston to move with the speed v_{cyl}, according to

$$v_{cyl} = \frac{Q_{cyl}}{A_p} \tag{34}$$

Where A_p is the surface area of the piston inside the cylinder.

With the piston area A_p being constant, the pressure inside the cylinder chambers depends on the total force acting on the cylinder. As the system is operated in closed loop setup, the important parameter is not the absolute pressure inside the chambers, but the pressure difference p_{diff} between the chambers, given by $|p_{cyl,A} - p_{cyl,B}|$. The pressure is

$$p_{diff} = \frac{|F_{PTO,A} - FPTO,B| + F_{fric}}{A_p} \tag{35}$$

Ideally, the pressure difference should not change the dynamics of the system in any way. Increasing PTO force will increase the pressure in the cylinders, and thus across the pumps. This, in turn increases the torque on the hydraulic pump shaft. As a safety feature, if the pressure increases too high, the oil is discharged through overpressure relief valves. The setting of those valves establishes a maximum pressure level p_{max} in the system. As the electrical motors connected to the hydraulic pumps are sufficiently powerful to supply enough torque to overcome the pressure difference up to p_{max}, the pressure levels should be irrelevant from a control engineering point of view.[87]

6 Testing Methodology

This section introduces the control method currently used to operate the wave simulator, and the data acquisition and processing used to derive wave input data for the experiments. The measurement methodology used for the results is also discussed.

6.1 Currently Implemented Control Method

The wave simulator is currently controlled with a feed forward control loop. The cylinder speed is calculated independently of the controlled process, and ahead of time with a separate hydrodynamical modeling toolset. The current control method is not grounded in the understanding of the dynamics of the hydraulic system. It is purely feedback driven controller. The original control algorithm was designed through intuition and experimentation, rather than rigorous modeling work.

The currently implemented control system is illustrated in Fig. 26. Two distinct parts are identified, hydrodynamic modeling and the wave simulator process. The hydrodynamical simulation done as a batch operation before the actual wave simulator process is involved. The input data set for the hydrodynamical calculation is a 30-minute wave elevation time series. This data is used as an input for the WaveDyn hydrodynamical modelling suite. THe hydrodynamical properties of the panel are imported to the simulation from WAMIT modeling software. A non-linear time domain analysis is performed, and the force equation in Eq. (15) is solved at each time step. The PTO is modeled as a linear velocity-to-force conversion ratio. This gives a rough approximation of the PTO response to panel movements, and this force is fed back into the hydrodynamical simulation. The result of this simulation is a time series of panel angles every 100 milliseconds, for a total of 18000 angle values.

This list is transformed into a time series of drivetrain positions with the kinematic model of the drivetrain mechanism.

This drivetrain position list is used as an input for the primary control loop. Due to real-time data transfer limitations, this list is transferred to the PLC ahead of time. The PLC is continuously running the control loop, performing each iteration in 20 milliseconds. As the reference list is in 100 millisecond increments, the speed is calculated with linear interpolation.

$$x_{pref} - x_{cref}/0.02 = v_{ref,v} \tag{36}$$

The speed reference is compensated with position reference, scaled down to 0.05:

$$x_{cref} - x_{act} * 0.05 = v_{ref,x} \tag{37}$$

The controller is essentially trying to match the speed profile of the input reference, but a compensation term for the position is also required. In theory, the system would only require the velocity of the cylinder to be correct, as the hydraulic cylinder is nearly linear in around its operational point. Emulating the speed of the panel at all points would be sufficient, and the position could be ignored. The position of the

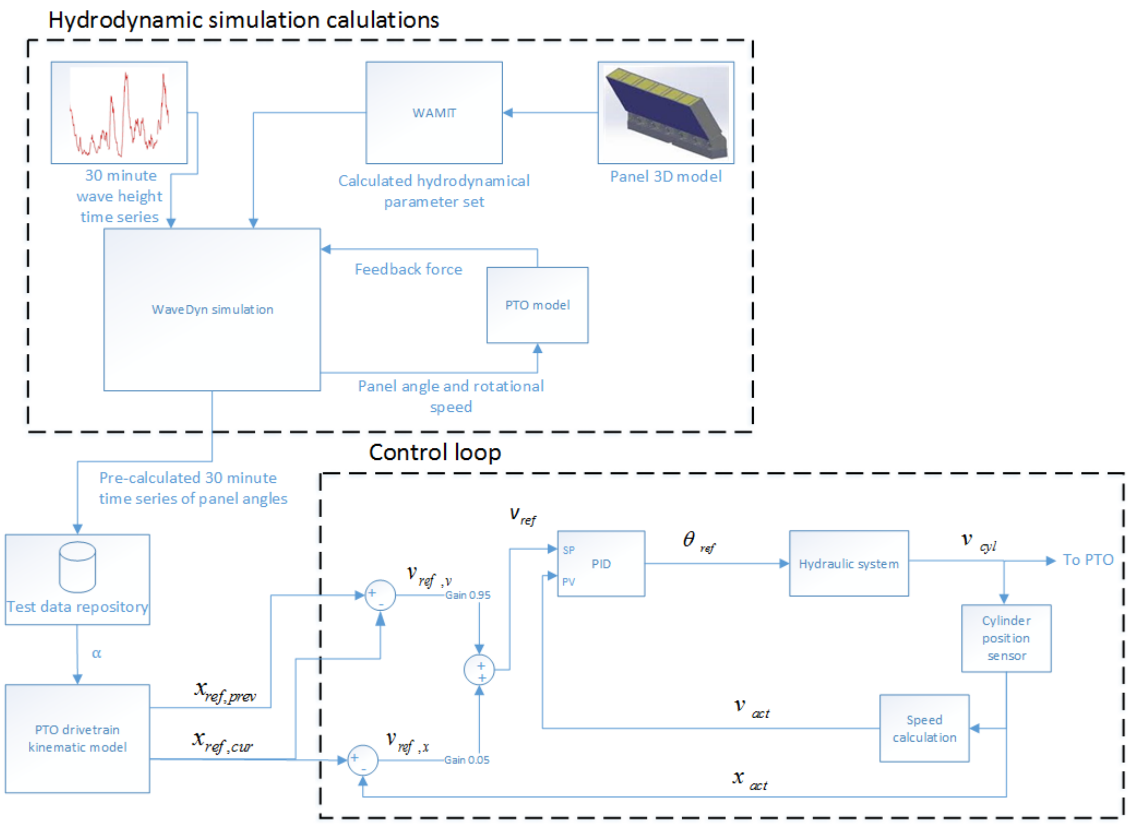

Figure 26: Diagram illustrating the components of the current wave simulator control system.

hydraulic cylinder is used as a part of the control loop because the both the wave simulator and PTO cylinders have mechanical hard stops at the ends, and during normal operation the PTO will be controlled in a way that prevents the cylinders from reaching this hard limit. The panel movements are centered around zero angle, which corresponds to centered position of the wave simulator cylinder.

THe hydraulic pump controller cards will internally adjust the control voltage for the current outputs, which are used to adjust the swashplate angle of the hydraulic pumps. Adjustments to the swashplate angle directly change the oil flow, with a delay arriving from hydraulic oil compressibility and swashplate controller inherent slowness. [101]

The cylinder current position x_{act} is measured by linear encoders, and is recorded by the automation system at a sampling interval of 10 milliseconds. From concurrent position measurements, the cylinder actual speed v_{act} can be calculated. These signals are used as a feedback for the controller.

6.2 Input Data

Producing the input data for the wave simulator requires accurate measurements of actual ocean waves. A plethora of such measurements are available, as the offshore and shipping industries also have a need for accurate wave data. Typically, wave measurements record data in a spectral density format according to mean values during the measurement period of approximately ($10^3 s$). This gives out comparable, singular numbers that measure the average amount of energy in the waves accurately. For the context of wave energy generation, the shorter scale variations like wave periods ($10^1 s$), and the interval between wave groups ($10^2 s$) are also very important. This is why time series data is necessary for the testing of wave energy converters.

Satellite altimeters use a radar to send pulses down from the orbit into the ocean surface, and then measure the shape of the leading edge of the leading pulse. With proper interpretation, signals from these satellites can provide significant wave height measurements around the globe. Such satellites have been deployed for decades, and the data they provide has been validated against buoy measurements. However, only the significant wave height and no other wave climate parameters can be directly measured from satellites.

From this enormous amount of data, accurate global wave models covering the entire globe are readily available. These models can provide full wave climate characteristic hind-casts all around the world, and have proven to give accurate results in most parts of the world. Combining models with real-time satellite altimeter measurements can also produce wave climate predictions days in advance[102].

However, these models only provide significant wave characteristics, meaning that they do not give full waveform information, but only the characteristics of an average wave. Simulation and testing requires the full waveform, as energy of the individual waves can be up to an order of magnitude greater or smaller than the average. Generating a time series of instantaneous wave elevation against time requires local, high frequency measurements [103].

Most accurate local wave measurements are made with a floating, heaving, directionally sensitive buoy moored at the ocean floor. Such devices can produce very accurate local wave climate data, allowing to calculate complete wave data including the height, period, phase and the directional spectrum. Such devices are, however, costly to install and maintain, and can feasibly be only installed at a few key locations.

A more cost-effective method to measure wave parameters include bottom-installed pressure sensors and acoustic Doppler units. A surface-facing pressure sensor is very simple and cheap to implement. From the pressure measurement, the height of the water column above the sensor can be calculated. Arranging these sensors into an array enables the measurements to be directionally sensitive, enabling the directional spectrum to be calculated. The surface elevation profiles acquired by pressure measurements alone are usually comparatively poor in a shallow-water environment, however, due to water currents caused by the surge effect affecting the pressure measurements.

Sonar-based devices use the fact that the sea surface is highly reflective for acoustic waves. Doppler-measurement-based devices can simultaneously measure the mean current to compensate for it, producing more reliable results. Acoustic devices usually also include pressure sensors to further increase accuracy by sensor fusion filtering. Using multiple beams facing different orientations enable directional spectrum to be measured using a self-contained installation. These measurements are shown to be well in line with buoy-based ones [104].

The primary data used for the test rig was recorded at the coast of Peniche, Portugal during the operation of the previous generation prototype. Measurements were done using an AWAC (Acoustic Wave And Current Profiler) device developed by Nortek A/S. The device was installed some 30 meters away from the WEC to eliminate the effect the device has on the waves. It is self-contained, and only requires a single device to be installed at the ocean floor. The device uses the Maximum Likelihood Method (MLM) to estimate the directional spectra from the elevation measurements.

Choosing a commercially available product was very clear, as developing our own method would have been costly, and without any proven operational history that the commercial products have. The primary purpose of the measurement was to measure the power carried by incoming waves, which is vital while analyzing the WECs ability to convert incoming wave energy into electricity. It also provided the stochastic wave characteristics used in the design, simulation and laboratory testing of the current prototype, as it matches the wave climate the prototype will be installed in.

6.3 Hydrodynamic Modeling

Determining the control signal needed for the wave simulator requires calculating the effects of the measured waves have on the panel and the PTO. As mentioned before, this interaction is not a straightforward one, and requires calculations of complex hydrodynamic interactions. Operating in the frequency domain and assuming that the body motions are small in comparison to the wavelength (i.e. linear wave theory) would greatly simplify the calculations, and allow an analytical solution to be found.

However, in our case the non-linear effects are judged certainly to be significant, and a time-domain solution needs to be implemented.

Panel methods, also called Boundary Element Methods (BEM) are computational methods used to solve partial differential equations. This method has been successfully applied in the context of wave energy conversion since the early days of wave energy research in the 1970's, and the modeling methods have since been commercialized by multiple companies. In essence, these computational methods break the geometrical shape of the surface interacting with the hydrodynamical medium into a finite number of panels, and then attempt to solve the potential flows and pressures caused by the incoming waves in respect to these model surfaces. These methods allow for time or frequency domain analysis [82], time domain being mandatory for devices where the non-linear effects are deemed significant, including the WaveRoller.

The toolchain used for the hydrodynamic calculations during the development of the panel design includes WAMIT and WaveDyn. WAMIT, developed by WAMIT Inc., is a commercial hydrodynamic calculation software used to solve the hydrodynamical properties of a given geometry of a submerged body using the panel method. The hydrodynamic properties of the geometry were used as an input for WaveDyn, a commercial software package for the design of wave energy converters, made by the maritime certification company DNV GL. WaveDyn is used to simulate the system in time domain, taking into account non-linear hydrodynamics and wave conditions. The performance and validity of this toolchain in comparison to other choices has been discussed thoroughly in [5], [5]

Commercial tools were used as they are available and rapidly deployable, as developing our own tools would have been very time-consuming. The same toolchain was used to design and model the previous generation prototype device, and after the sea trials the measurements acquired during operation in 2014 were compared to the numerical simulation results [105]. A suitable agreement was confirmed, giving validation for using this methodology to design oscillating wave surge converters. Similar simulation tools have also been used by another company designing a device with the same basic operational principle.

Modeling the power capture in moderate sea states is the main goal in optimizing the energy capture, as the most energetic sea states are relatively rare, and contribute only a small fraction of annual energy. Models for the extreme sea states are important in verifying the survivability of the device, however[7].

6.4 Measurements

Measuring process variables is performed mostly with analog pressure, temperature and position sensors. Automation systems for the wave simulator and the PTO each contain their own integrated digital to analog conversion circuits, and the measured values are passed on to the automation programs. Sampling rate of these measurements are limited by the performance of the automation processor, as the measurements are read only when the program begins another scan cycle. These measurements are mainly used for control. They are transferred to the operator room computers via TCP/IP drivers to be shown with the SCADA system. Process

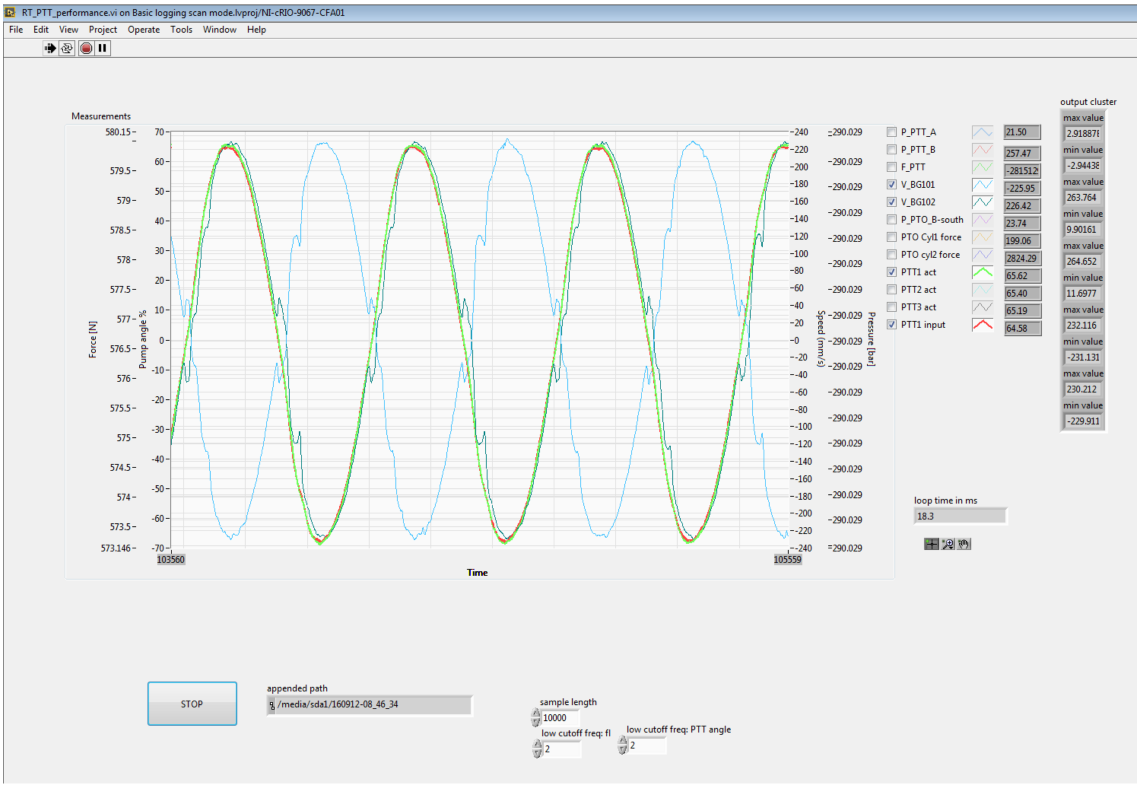

Figure 27: Screenshot from the Labview application used to recording the measurements for this work.

variables measured this way can also be logged.

Measurements done for this work require values measured from both the wave simulator and PTO systems. Additional, measurements currently not performed for either automation were also required. Adding and removing measurements from the automation systems would require changes to the automation system program. Unnecessary automation program changes are avoided whenever possible, to ensure system stability and code integrity.

To ensure synchronization between the two systems, and also to avoid changing the automation system every time a new measurement is required, a separate measurement system was installed. The platform used is a National Instruments CompactRIO platform, an embedded computer running a real-time Unix operating system. Separate pressure and position sensors are installed for the measurement system, and the signals are converted from analog to digital with the pluggable measurement modules in the cRIO computer. Two cRIO units are placed in the test facility area to simplify cabling. The data recording and visualization program, in Fig. 27 is built using National Instruments Labview software. The PC hosting the Labview application is in the same operator room as the wave simulator and PTO control systems. Data from each cRIO is syncronized with the Labview application using Ethernet communications through series of industrial switches.

7 Testing Results

This chapter presents measurements that highlight the performance of the currently implemented wave simulator controller, draws conclusions about its performance and weaknesses, and presents a new controller implementation and the tests used to identify system parameters used for the new controller. Based on these findings, the testing results identifies some control method changes that would enable the test bench to more closely emulate the actual forces and movements caused by the waves in the WECs actual operational environment. Testing results for the new controller are not presented, as the new control was not possible to implement at this time.

Of the goals outlined in the previous chapter, the force controller testing and tuning is the main motivation behind this work. The current controller is know to be incapable of precise force control, and one of the tasks of this work is to present a controller method capable of force feedback and control. To achieve this goal, the system dynamics are analyzed, and based on the performance of the currently implemented controller, an improved control system is proposed. Other test bench goals are not given a thorough analysis, but are discussed in brief in chapter 8 to give a more complete view of the test facility operations.

7.1 Current Control Method Results

The main control variable of the wave simulator is the cylinder speed v_{cyl}. This is the physical connection to the PTO being tested. The cylinder speed is measured with linear transducers mounted on the cylinder. The measurements are done individually from both ends of the cylinder, and the average of those two measures is used. Linear transducers exhibit high-frequency jitter, and as the intertia of the cylinder causes the actual movements to be quite slow, the position measurement signal is filtered with a 2 Hz low-pass filter. To calculate the speed from the position, the difference between two most recent position measurements is divided by the sampling frequency of 50 Hz.

Samples from the testing results of two stochastic sea states are presented here, as they punctuate the characteristics of the controller. The most important parameter for the controller to get right is the cylinder velocity. The force at the drivetrain is adjusted by the counter-force produced by the PTO hydraulics, and the wave simulator is powerful enough to match any force level caused by the PTO. This leaves the drivetrain velocity as the only relevant parameter, and the only interface between the wave simulator and the PTO.

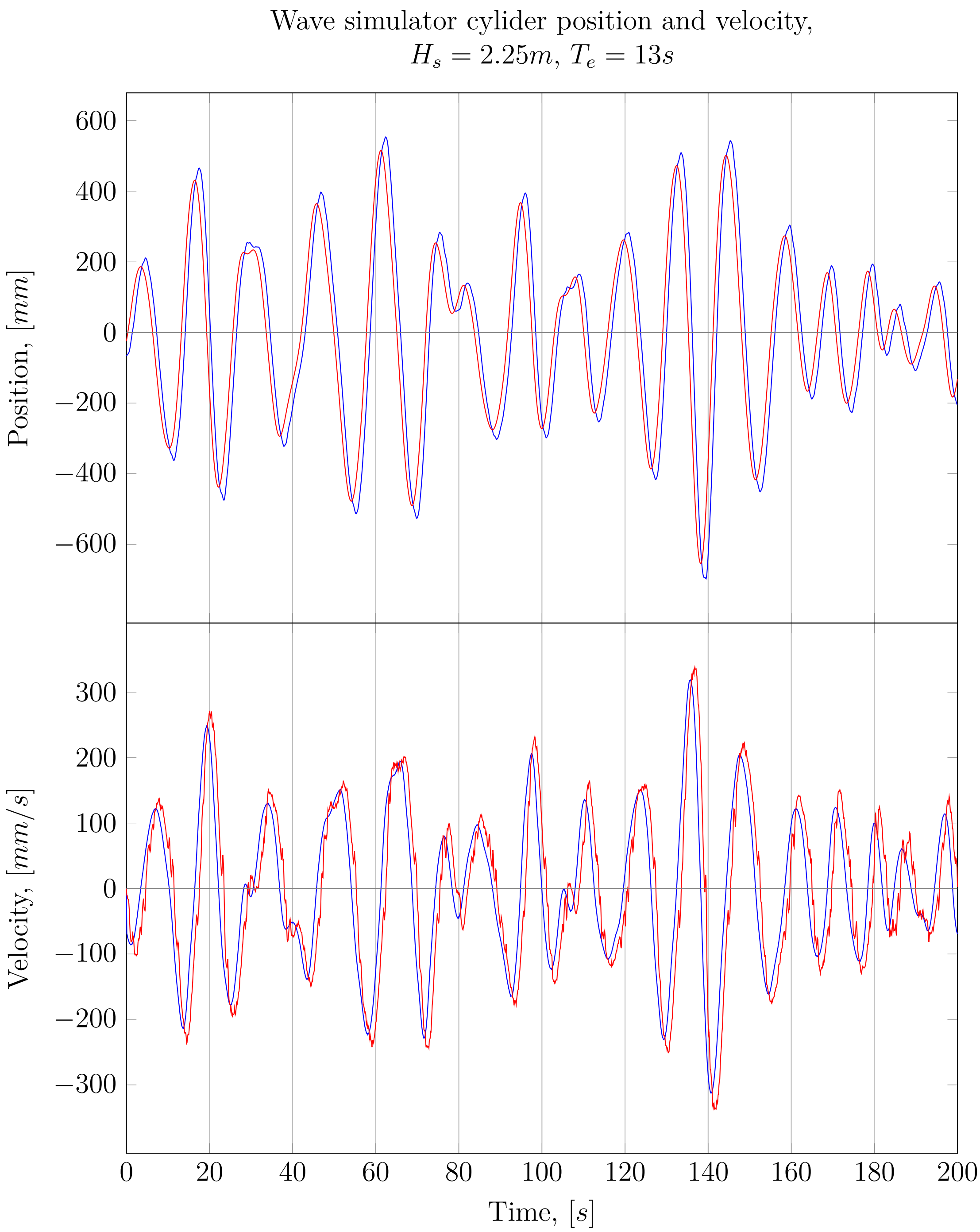

Figure 28: Time series of wave simulator cylinder position and velocity references and actual values at a moderately powerful sea state input data.

In Fig. 28, the stochastic wave input data is from a moderately powerful sea state with a significant wave height of 2.25 meters and an energy period of 13 seconds. From the table in Fig 7, this is identified as a moderately high-power wave. Both the position and the speed of the cylinder replicate the profile of the reference signal, but are delayed approximately 1.2 seconds. This delay is a combination of controller integrator term delay, fluid compressibility and inertia in the hydraulic system.

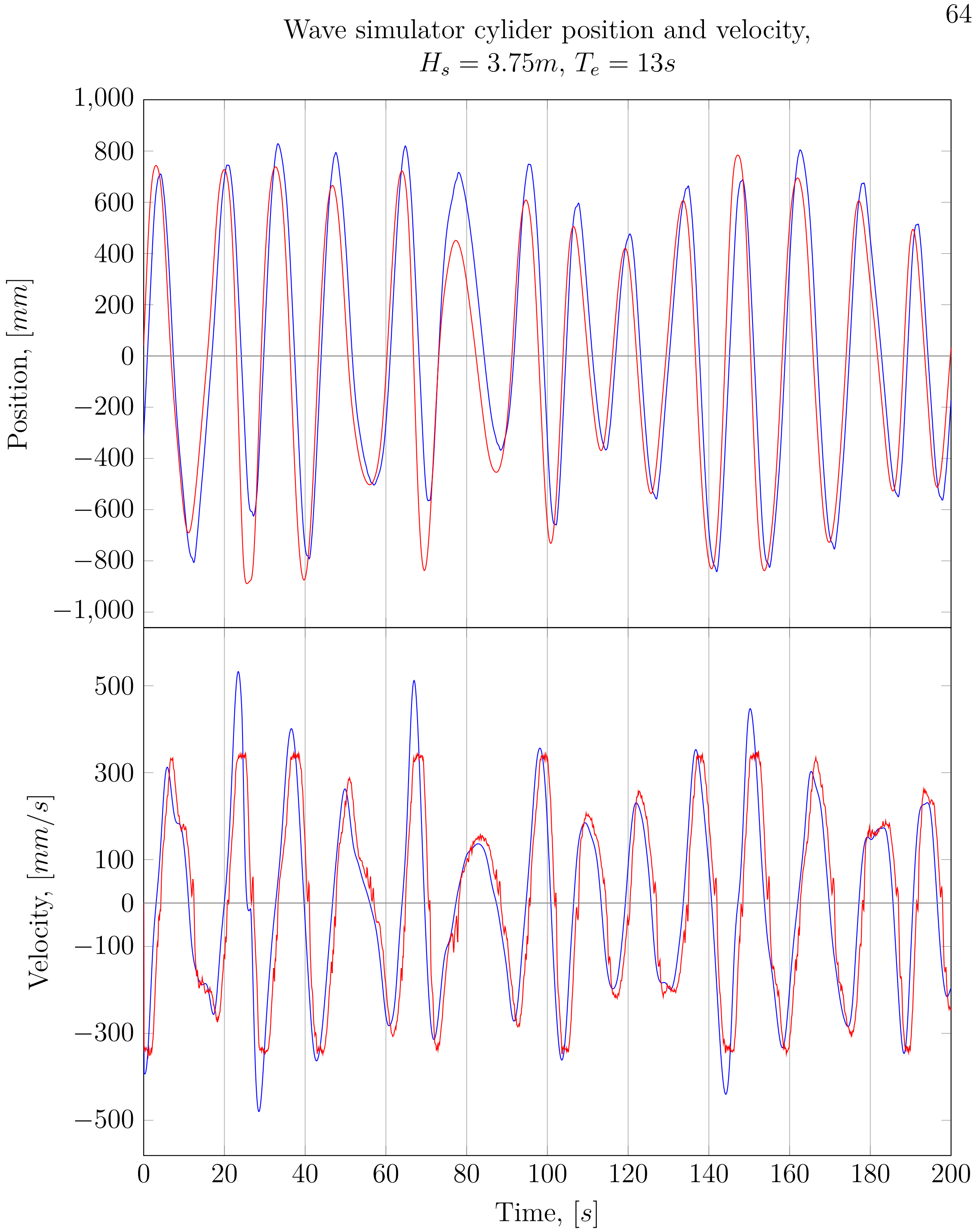

Figure 29: Time series of wave simulator cylinder position and velocity references and actual values at a very high power sea state input data.

In Fig. 29 the stochastic wave input data is from the very powerful sea state of $H_s 3.75m$,$T_e 13s$. From the table in Fig 7, this seas state and those even more powerful represent less than 5% of the annual sea states. The same delay component of about 1.2 seconds as with the more moderate sea state is present. The maximum cylinder velocity is reached, and the actual value cannot keep up with the reference. As a result, the position drifts far from the reference.

7.1.1 Evaluation

The current controller has been successfully used for over a year of testing, and from these tests and casual observations, it had been successful in some most respects. Most importantly, the current controller has allowed us to safely test the main focus of the facility, the PTO system. The exact replication of the input data set was not a design goal for the controller, as testing the overall functionality was deemed more important for this phase in product development than exact one-to-one hydrodynamic correspondence.

The cylinder speed actual value is lagging behind the speed reference by about 1.2 seconds. As there is no feedback from the hydraulic system, this is not problematic. From the point of view of the tested PTO, the important factor is the cylinder speed. Visible from the velocity graphs is that the velocity profile is reproduced faithfully. The delay is also consistent, with multiple runs with the same data producing nearly identical results.

At low power sea states, the output cylinder position, and thus the velocity, reproduce the profile of the input data. This has been the most important task of the wave simulator. The velocity profile is reproduced after a delay, but as the system is not sensitive to this delay, it is not problematic. The position also is lagging approximately 1200 milliseconds behind the reference. As the PTO system is almost completely insensitive to the position of the cylinder, unless it hits the hard limits at ether extreme, this is not seen as problematic. As the system dynamics are fairly slow, a simple feedback PID controller with correctly tuned parameters is able to perform sufficiently well.

At higher energy sea states, the controller does hit the physical limits of the pump units, as even 100% reference is not enough to match the speed requirements set by the input data. The PID component of the controller saturates the pumps, and does a somewhat fair job in reproducing the parts of the input data that are within its reach. As the velocity is not able to keep up with the reference, the position reference and actual value are not in agreement at all. It was known beforehand that the wave simulator would be unable to reproduce the most powerful sea states, and this was accepted as trade-off between accuracy and financial commitment. Although it cannot reproduce every sea state completely, it is still the most powerful wave energy test bench device in the world.

The pre-calculated input data set is completely insensitive to the actual forces or movements of the PTO, as the calculations are done without any interaction to the physical machine. As a result, the wave simulator controller is only very weakly responsive to the force control applied by the PTO. This means that testing the PTO force controller is practically limited to mechanical and hydraulic evaluation, as its potential to increase power capture cannot be modeled by the wave simulator. In other words, the wave simulator is sometimes applying unrealistically high power, and is not responsive to the hydrodynamic effects that the PTO counter-force would cause on the panel.

Overall, the controller has served its intended purpose fairly well. However, some undesirable characteristics have been identified:

- System is insensitive to PTO force at run time. It relies on the simplistic PTO model used in the hydrodynamical calculation, and does not reflect the actual system dynamics of the PTO. This makes force control algorithm performance testing impossible.
- Both the speed and position actual values are lagging approximately 1.2 seconds behind, although in a reproducible and reliable fashion. Further development requires more strict response from the controller.
- The hydrodynamical calculations are not done in parallel to the process, and hydrodynamical effects caused by the PTO on the panel are not modeled at all.
- The control system is very specific to this single application, and can only handle 30 minute pre-calculated data files.

To rectify these shortcomings, new control design is to be designed.

7.2 Swahsplate Pump Position Control in Literature

Controlling swashplate pump-driven hydraulic systems with cylinders as the actuating device has been investigated in some academic articles.

In [106], the control of the swashplate angle in a very similar pump design is analyzed, and it is concluded to be reasonably linear within the the operational range.

In [107], a similar setup is presented, with two hydraulic systems pushing against each other. The force control of such system a is seen as too unpredictable and nonlinear to be modeled accurately, and a grey, self-tuning controller is used.

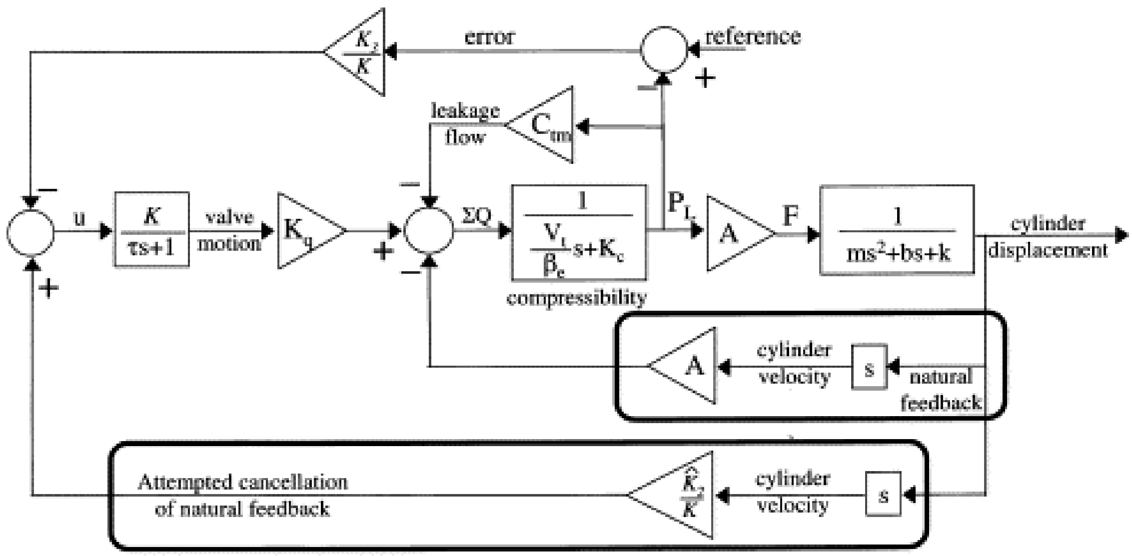

Figure 30: Simple hydraulic control system for a closed loop cylinder position control with swashplate pumps in a very similar setup. [108]

The hydraulic system presented in [108] is a close match for our setup, although smaller in scale. The control system they have designed accounts for pump leakage, oil flow velocity related slowness, and the oil compressibility. Method they use to compensate for the inherent system stiffness causing the delay also seen at our system is to predict the future cylinder position from current position and velocity of the cylinder.

The very well documented control method used for the Wavestar PTO test bench (Fig. 19) is similar to the Järvenpää setup up until the hydraulic control system. They used open loop configuration, where the pumps are unidirectional, return oil is discharged back into oil reservoir, and the cylinder flow is controlled by a valve. The closed loop system used at Järvenpää is in contrast with this, as the oil outflow from cylinders is diverted back into the pumps. As the variable displacement pumps handle the flow control, there are no valves controlling the oil flow. The Wavestar controller is used as a source of inspiration for the calculation of oil flow reference, however.

7.3 New Control Method

The new controller is presented in Fig. 31 is designed to correct the flaws found in the old controller. Particularly, the hydrodynamic simulation is to be performed

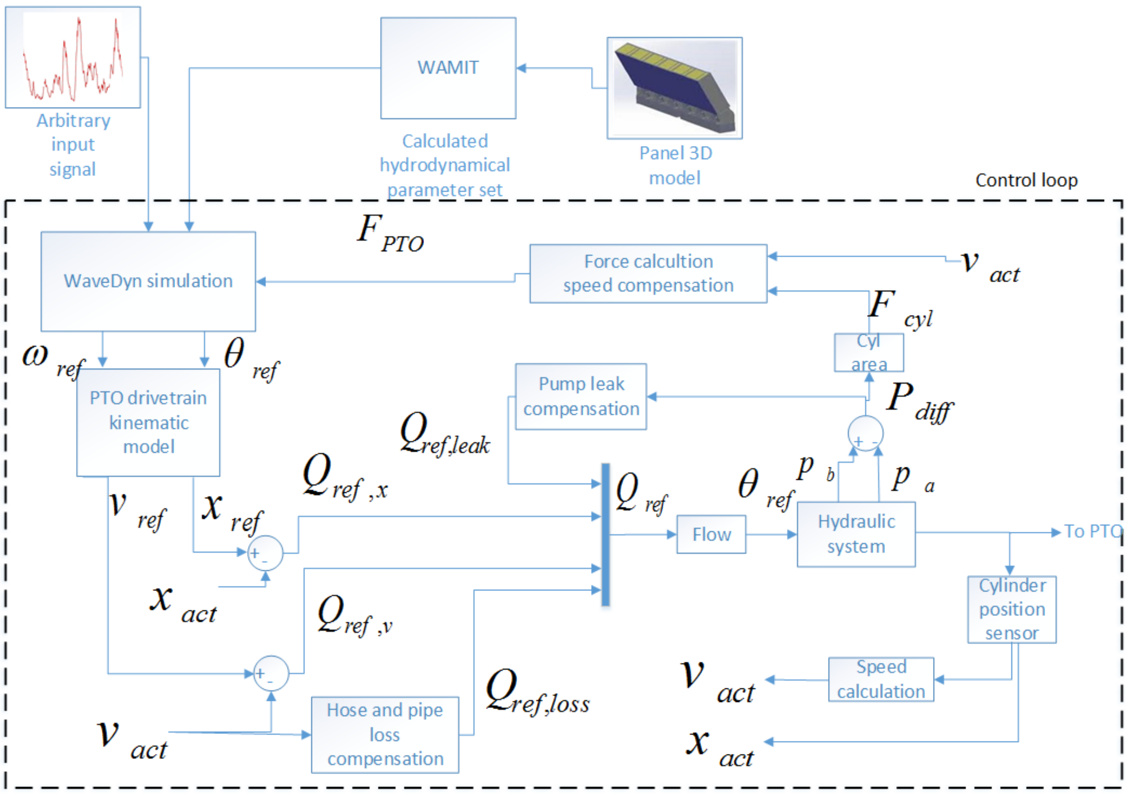

Figure 31: Conceptual control diagram for the new control method.

on-line, in contrast with the previous solution of calculating data sets beforehand, and representing PTO dynamics with a simplistic linear model.

Incorporating the hydrodynamical simulation and the physical plant together allows for testing the exact performance of the force control method, which is seen as an important factor in increasing power production without increasing capital costs. Feeding the measured PTO counter force back into the hydrodynamic model allows the simulation to take into account the braking of the panel movements caused by the PTO. A simplistic hydrodynamic calculation could be performed on the PLC, but developing an accurate model of an OWSC panel and its interaction with the waves from scratch would require great amount of verification work before any conclusions could be drawn.

The goal of the new controller is to be easily adaptable to test different types of wave energy converters. The current control arrangement is restricted to 30 minute time series in a very specific format, and cannot accept inputs in a different format, or a different type of hydrodynamical model. The calculations are dispersed between a number of computer systems, and the specifications of each step are unclear, and unable to be utilized or modified from a separate system. To facilitate this requirement, all of the components of the control should be implemented as interfaces, with clear, documented, physical meaning to their inputs and output.

Hydrodynamic modeling solution already exists in the WaveDyn software that is used to calculate the current input data. The WaveDyn model is also confirmed to be accurate by comparing models to actual measurement data from scale tests and the demo device in Peniche. Incorporating WaveDyn to the control loop in real time would require a low level access to the simulation software, which is not readily available. From correspondence with WaveDyn developer DNV GL: "WaveDyn has never been used in such a configuration, and allowing this behavior would require non-trivial amount of work from our end". In addition to this, the software is too computationally expensive to run at the PLC, so additional computing hardware with real time communication to the wave simulator automation system would be required.

Simulation and calculation software running on a dedicated modeling PC is to be used to run the hydrodynamic simulation. A low-latency, high availability communication between the wave simulator PLC computer and the simulation PC is required. A network-routable protocol is required, as there is no direct cable connection between the control room and factory floor. Profinet protocol is seen as the most relevant one, as the same protocol is already used for fieldbus communications between automation systems.

The drivetrain kinematics simulation is decoupled from the hydrodynamic calculations, and from the automation PLC program. Running the drivetrain kinematic calculations in a separate process allows for easier adaptation of the test bench for different kinds of drivetrain constructions. The PLC program code does not need to be changed to test different types of drivetrains. A Matlab Simulink-based solution is seen as optimal, as Matlab has great amount of built-in support for hardware-in-the-loop, industrial communication and process interoparation.

The old controller used only position reference as an input, and the velocity reference was calculated from the derivative of position. This implementation works correctly as long as the time series format for the positions stays static. However, simulation loop time might not be static, and the precise time between position references could be variable. For this reason, the velocity and position references are both used as outputs for the kinematics simulation.

The oil flow reference is a sum of the references from velocity and position differences $Q_{ref,x}$ and $Q_{ref,v}$, the pump pressure difference compensation terms for pump leak oil flow $Q_{ref,leak}$ and the velocity-dependent loss $Q_{ref,loss}$. The coefficients between these components are to be determined through testing.

7.4 System Parameter Identification Tests

To establish parameters for the new controller, isolating tests are performed. The pump controller circuit performance is tested by comparing inputs and outputs of the control circuit in Fig. 32. To approximate the flow loss caused by high flow rates, the relationship between swashplate angle and wave simulator cylinder speed is established.

7.4.1 Pump Controller Performance Test

As discussed in the previous chapter, the primary control for the hydraulic pumps is an amplifier card that converts the given pump angle reference into swashplate angle reference, and then corrects for errors in swashplate angle with a PID controller. Each pump is controlled by a separate controller card and every controller is given the same reference. The input signal is a test input signal from the wave simulator PLC formed by hand-crafting a wave simulation input data to produce abnormally fast 'waves'. Modifications of the PLC code to allow arbitrary input signals would have required interfering with the safety automation logic, and was deemed unnecessary.

The pump controller performance test results are presented in Fig. 32. The controller card used to drive the solenoids on the main pump position cylinder servo valve has been tuned to match the pump parameters, and is shown here to perform well. The actual values from all three pumps are lagging 30 milliseconds behind the reference signal. This signal has a period of about 1.4 seconds, much lower than the shortest wave periods found in nature of about 5 seconds. The pump controller cylinder can thus reposition the swashplate from maximum negative angle to maximum positive angle much faster than the system performance requires. The pump swashplate control circuit and swashplate positioning cylinder system are creating a delay of about 30 milliseconds, and are not a significant contributor to the total system delay of 1.2 seconds.

The pump displacement controller is fast and accurate in the operating region of the wave simulator.

7.4.2 Pipe and Hose Loss Measurements

From experience, it is suspected that the hydraulic hoses, pipes and the connector blocks between hydraulic pump units and the cylinder are causing the oil flow to turn

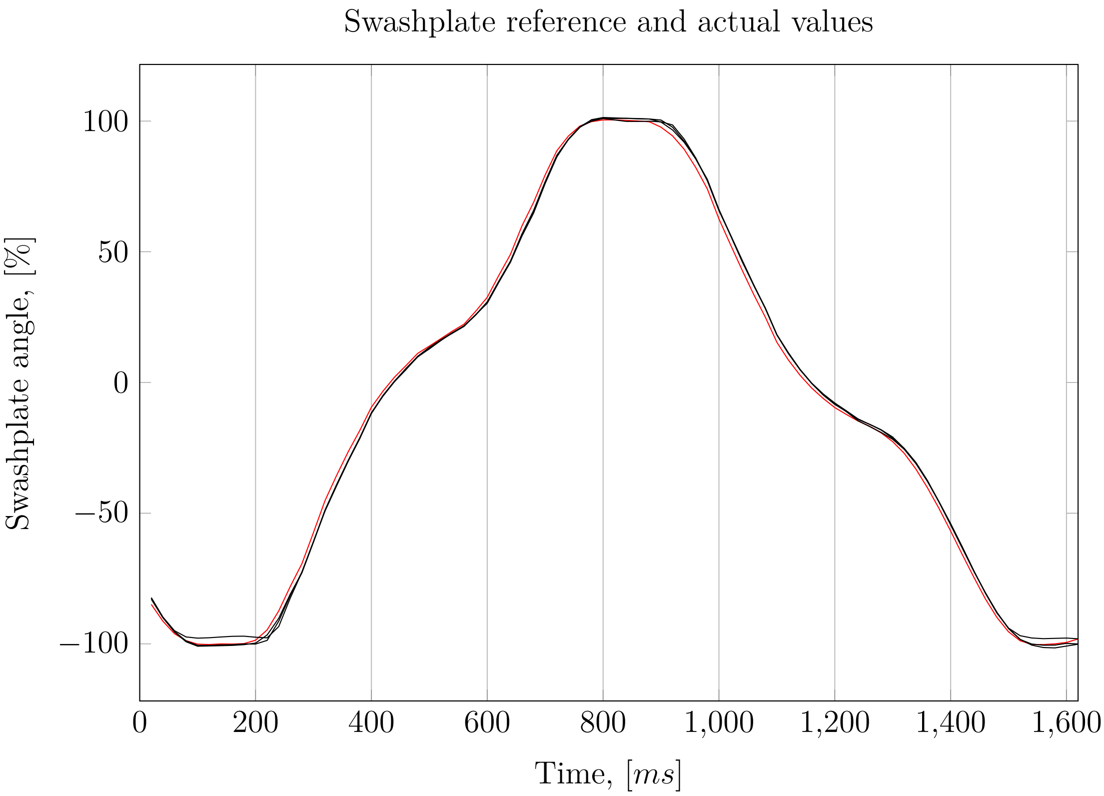

Figure 32: Swashplate angle reference (red) and actual value from each pump unit (black).

turbulent at high flow rates. Turbulent oil flows cause additional friction within the pipelines, and leads to pressure losses and reduced power throughput. To measure the actual effect of the pipelines, the actual oil flow is measured. As the system has no inline flow measurement devices, cylinder speed is used to measure oil flow. As the cylinder area is known, oil flow can be calculated from position.

The test is done with no PTO load. Starting with only one pump active, the cylinder is driven from end to end with maximum angle limited to a specified value. The average cylinder speed is measured for each direction. The average is taken from time series values where the swashplate angle feedback is equal to the maximum angle limit. The test is repeated five times, at 20% maximum angle limit intervals. Entire test is then repeated for 2 and 3 pumps active. Samples are taken at 50 Hz frequency.

The results for the flow rate test are presented in Fig. 33. The overall correlation between the predicted and actual flow rates is good, and not dependent on the number of pumps. This suggests that the flow is not constricted by the collector block, but individual hoses connecting the pipes. At the maximum swashplate angle, about 5% reduction from the expected to actual flow is recorded.

However, a strange bias between the positive and negative directions is noticed. The oil flow in positive direction is systematically about 28 l/min lower than the negative side. This suggests that the zero point for the controller is incorrect. The zero can be adjusted by turning a potentiometer on the controller card for each pump (see Fig 25). The zero points for the pumps were recalibrated multiple times, but the bias persisted.

Adjusting the zero point is done with the pump running, adjusting the potentiometer until the pump produces no flow. Due to the construction of the amplifier card housing, the potentiometer cannot be turned while the card is installed, unless an extender card is used to put the adjustment knob in view. It was discovered that the extender card, used to raise the controller to enable the potentiometer to be adjusted, picked up interference from the nearby power source, and additional resistance caused by the longer circuit path. To rectify this, the flow caused by the pump zero point misalignment was measured without the extender card installed, and then with the extender, the flow was adjusted to negate the misalignment.

After these adjustments, the flow rates for both directions were equalized.

7.5 Conclusion

In this chapter, results from the current controller were analyzed. The controller is seen to be sufficient for most types of testing, but a number of potential improvements were identified. To improve the controllers agreement with the real world forces and velocities caused by the ocean, a new controller is proposed. The main changes are a feed-forward control principle, where the oil flow reference is calculated based on the plant model instead of the purely feedback-based oil flow control used now. The hydrodynamic model is coupled with the physical plant, creating a much larger control loop.

The costs for the software licenses, additional hardware, man-hours and system downtime that would have been required to implement the new controller were deemed too great for this point in the product development cycle. Running continuous tests at the facility to reveal flaws before the marine version is commissioned was seen as a higher priority than to implement the controller changes at this point.

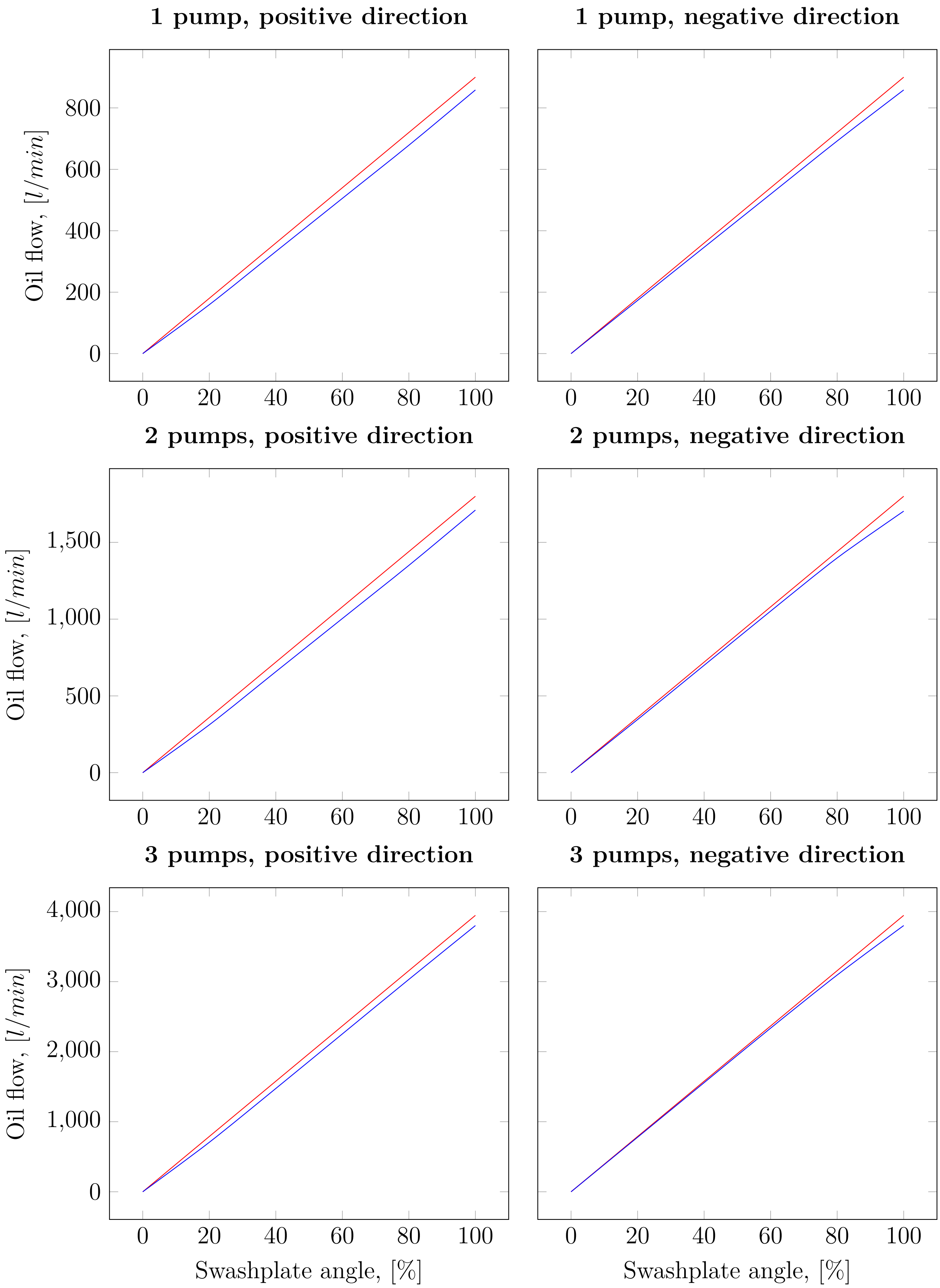

Figure 33: Original flow rate measurements. Predicted flow rate in red, actual flow rate in blue.

8 Discussion

The race for the first commercially successful product capable of generating electrical energy from ocean is on. As the energy resource is still untapped, the first device to deliver feasible and economically viable renewable electrical generation has a huge market potential. The road towards an economically viable device has been a rocky one. The decades of theoretical work, hundreds of design concepts tested and many design companies failing without being able to produce a financially viable product paints a grim picture of the entire industry.

Avoiding having to test devices in their actual operation environment, the ocean, is a major cost saving measure for ocean energy research projects, as ocean operations require special equipment and expensive techniques. Simulational tools and small scale hydrodynamical tank tests form the backbone of the design process, and the majority of conceptual work has to be done at this stage. However, simulations and small scale experiments cannot fully predict the behavior of a full scale system, as the sources of non-linear effects and their magnitudes are difficult to identify and model. This problem is particularly prominent in modeling the power take-off part of the wave energy converter, and scaled-down versions of PTO designs offer a poor representation of the design challenges for a full scale PTO. This is why many companies who have reached advanced stages of the product design process, and are preparing for the first full scale device for ocean deployment, have chosen to perform dry experiments with their PTO designs, using no actual water waves for the testing but some other type of power system to emulate the wave interactions.

As the technology used in WaveRoller or the test site for it have not been presented in academic studies in the same degree as some other WEC design concepts, a large proportion of the work is dedicated to explaining the fundamentals of the technology and the testing concepts. The wave energy device test facility built at Järvenpää aimed to be a product development tool for a particular wave energy power take-off module. To achieve this, several goals were set for the facility, given in Chapter 6. The facility at Järvenpää has been, and still is veiled in secrecy due to intellectual property concerns. This work attempts to uncover some of the findings done during the design and operation of the test bench. It is the first publication discussing the components and methods used by AW-Energy team at Järvepää, and it gives an overview of the testing facility's operation. General advice for anyone seeking to construct such a facility for their wave energy test device is offered, and motivation behind some of the design choices made is presented.

Some subsystems of the original PTO design draft were not fully functional. The hydraulic circuit had some unforeseen design flaws, including too stiff valve springs and insufficient oil flow rates at certain lines. After some initial tests with very low power levels, additional problems with the hydraulics were discovered that prevented safe operation with high power levels.

Through small improvements and modifications, the system power levels were gradually ramped up. As the automation system was initially designed for the original system, every change in the hydraulic and electrical system caused design changes in the automation. This process of continuous integration of new improvements and changes slowly allowed to ramp up the power levels in the system. The automation system that controls the PTO was developed alongside the changes made to the physical system, and numerous gradual improvements have been made during operation.

After the initial challenges with the power unit were rectified, the actual testing campaigns could begin at full power levels. Testing runs using stochastic, measured wave data was used to establish the efficiency and power production capabilities of the device in different wave conditions. By using an adaptive controller that changes its parameters according to the wave input power was developed. By automatically modifying the automation program parameters on the fly, the power production at more extreme sea states was able to be improved.

Accumulator system used to store large amounts of hydraulic energy by compressing gas inside the piston accumulators is likely the defining feature of the PTO device. Unlike most other renewable energy technologies, this device can store power for up to 30 seconds of production, allowing the PTO to support the stability of the electrical network in a way that other renewable technologies cannot. The functionality and performance of this power storage mechanism were confirmed during the testing.

The test center at Järvenpää has been used extensively as a technology showroom. As AW-Energy is still in the product development stage, and dependent on external funding, it is of paramount importance to be able to show concrete results rather than just ideas and concepts. For this, the Järvenpää center has been a popular tour location for demonstrating the technology for potential investors, industrial partners and other associated parties. The official inauguration for the test site was held at 17.11.2015, and the guest of honor who pushed the button to start the machine was the President of the Republic of Finland Sauli Niinistö.

The WaveRoller device was awarded a technology qualification certificate by the international certification body Lloyd's Register in July 2016. The qualification process involved the Järvenpää research center to demonstrate the best effort to assess and mitigate potential risks in the design process. In future, the test center is likely to be used to further demonstrate quality and technical standard compilance.

Moving forward to the installation of the first 350 kW device with a PTO identical to the Järvenpää site, the test facility is likely to be renovated to account for possible design changes identified during the installation and operation of the device. The experience from the testing facility, and the simillar facilities others have constructed leads us to following conclusions about wave energy power take-off testing systems:

1. The testing facility has greatly increased our understanding of the hydraulic and electrical challenges present in wave energy conversion to electricity. The design has seen minor and major adjustments due to the findings done at Järvenpää. If the device had been constructed as it was originally designed, its viability for ocean deployment would have been questionable.
2. The design should not consist of just a single testing campaign, but be a continuous development process that iterates on the findings of previous test campaigns. Minor and major modifications might be necessary to the hardware and software side of the device.

3. Developing the control automation system with real hardware for testing changes online was of instrumental help in the development of the control systems.
4. Long-term testing campaigns can reveal issues not apparent from the shorter testing runs. Hydraulic systems are not usually designed for constant high pressure to low pressure cycles and high energy flows, and typical hydraulic design practices may not be sufficient. Designing such system using standard, off the shelf components proved to be more challenging than anticipated.

9 Conclusion

This work set out to provide an overview of the design process for a wave energy device testing facility. To outline the need for such a facility in the design process for a commercial wave energy device, the theory behind wave energy and the control problems is explained in the second chapter. The conclusion is that the most important unsolved problems are not theoretical, but practical problems in implementing the theory to design a viable product. Force control of the WEC is identified as a key area of interest. The next three chapters present a model of the power conversion chain for the WaveRoller device, potential test bench designs considered, view of other PTO testing facilities, and an overview of the world's largest wave energy testing facility constructed at Järvenpää.

The wave energy device test facility built at Järvenpää aimed to be a product development tool for a particular wave energy power take-off module. The test bench has proven to be able to simulate all but the most extreme sea states, covering over 95% of the annual sea states measured for the Peniche site. The currently implemented control method has been sufficient for the initial goals set for PTO systems testing. Some potential improvements were identified, and based on these, a proposal for a new, improved control method that integrates hydrodynamical modeling into the factory automation system. Originally, the results from implementing this new control method were intended to be included. The facility has been dedicated for testing the PTO design all the way until the marine version under construction is actually finished, and the time, licensing costs and man-hours that would have been necessary to implement the new control in time for this works deadline were seen as too high.

The testing facility at Järvenpää has been instrumental in the design process for the first commercial WaveRoller device. The fundamental principles behind the energy capture, transfer and production have been proven to be correct, but many of the assumptions of the exact characteristics of hydraulic and electrical systems were proven to be incorrect or insufficient. If the original PTO design derived from common industrial practices and simulations would have been constructed and commissioned, it would not have worked as intended. Most importantly, leakage-proofing the hydraulic system, and fine tuning the automation system would not have been possible without the test bench.

As of writing this, the test facility is used to perform accelerated deteriorating tests for the power take-off module, before its marine counterpart is commissioned in Peniche during 2017. For this test, constant maximum power is supplied from the wave generator to test the durability of the PTO components. For this design version of the PTO, the work at Järvenpää cannot bring many new design improvements, and we already have our sights set for the next iteration in design. Work on the test facility continues, and testing the inevitable evolution in PTO design would benefit from implementing the new wave simulator controller design presented in this work.

9.1 Future Work

The main unfinished area of this work is the actual implementation and testing of the designed control algorithm. Even though the algorithm is designed according to the guidelines presented for other WEC PTO test facilities and knowledge of swashplate hydraulic pump control theory, the actual implementation is challenging. Integrating the commercial WaveDyn software into the control system, or devising a new hydrodynamical simulation model are both options that need to be considered when the new control method is commissioned.

The system model of the PTO presented here is sufficient to understand the dynamics of the system, but it is missing some fine tuning around non-linear components, like hydraulic valves and pipeline pressure losses. It is not able to predict the power output of the testing facility precisely. The review of WEC models presented in [79] tells us that accurate and complete wave-to-wire model of WEC that can model the non-linear properties of all components accurately has not been done yet, for any kind of WEC, and deriving such a model is understood to be a large undertaking.

Additionally, as discussed before, the exact structure and control algorithms of the PTO itself are intentionally left vague in this work due to intellectual property reasons. Analysis of the PTO design, and especially critical comparison of its novel force control method to the large amount of research done on WEC force control offers many opportunities for research and advancement of knowledge in working, full scale wave energy conversion systems.

The marine WEC and its PTO is already under construction, and is due to be installed at Peniche, Portugal in 2017. The device is fitted with instrumentation, and as it is first of its kind, the amount of data to be logged is large. Comparing data from the actual production model to the test bench data is very important in verifying the results gained, and in correcting the assumptions made about hydrodynamic and hydraulic properties of the device.

The testing facility has produced large amounts of data, and the thorough analysis of that data is still underway. As this is the largest test bench of its kind, the academic community in universities and companies researching wave energy conversion systems would likely be interested in analyzing this data and presenting findings on it.

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