Internship at Deltares

Sander Käo

September 5th, 2014

Deltares
Enabling Delta Life

UNIVERSITY OF TWENTE.

Relevant information:

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Company: Deltares

Department: Hydraulic Engineering; Experimental Facility Support

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Location: Delft, The Netherlands

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Faculty & Program: Engineering Technology (CTW), Sustainable Energy Technology (SET)

Supervisor at University of Twente: Dr. Ir. P. C. Roos

Abstract

Climate change has led to the development of many renewable energy technologies. One of these technologies is wave energy, which is making great progress in becoming commercially feasible. One of the options to further improve the energy extraction from waves is to actively optimize some of the parameters of the wave energy converter. To do this a control system is required.

A scale model of a wave energy converter is designed and built for testing in a wave tank. For optimizing the wave energy converter a spring system and a dynamo with adjustable damping is designed and built. The wave energy converter with the adjustable devices is tested in a wave tank. The optimization is performed in a manual fashion. Results show that adjusting these parameters for a chosen sea state leads to an increased power extraction. Recommendations and ideas are given for building a control system which works in automated fashion.

Preface

From beginning of June 2014 to September 2014 I have been building, testing and optimizing a wave energy converter in Deltares. The 3 month internship project is one of the requirements from my MSc program of Sustainable Energy Technology from the University of Twente. The internship project is a continuation to my MSc thesis, which I also wrote in Deltares on the topic of wave energy.

Wave energy has always been a fascinating topic for me. The first time I heard about the concept of wave energy 7 years ago, I never imagined that one day I would have the possibility to build and test a wave energy converter. This opportunity was made possible thanks to my supervisor at Deltares, Dr. Ir. P. Wellens, who shares the same interest for wave energy. Even though he has a busy schedule, he always found time for answering my questions and provided good ideas throughout the internship. Furthermore I would like to thank all the other team members from the department of Experimental Facility Support. Without them this project would not have been successful.

From the University of Twente I would like to thank my academic supervisor Dr. Ir. P.C. Roos, whose encouragements and suggestions have always driven me in the right direction.

Sander Käo

September 5th, 2014

List of Symbols

Abbreviations:

RAO	Response Amplitude Operator
WEC	Wave Energy Converter

Roman:

A_{wl}	Area of waterline [m²]
b	Hydrodynamic damping coefficient [kg/s]
b_{PTO}	Mechanical damping coefficient [kg/s]
c	Restoring spring coefficient [N/m]
F	Force [N]
F_b	Buoyancy force [N]
F_g	Gravitational force [N]
F_w	Wave force [N]
F_{w_a}	Wave force amplitude [N]
F_{PTO}	External damping force [N]
g	Acceleration of gravity [m/s²]
h	Water depth [m]
H	Wave height [m]
H_s	Significant wave height [m]
H_{height}	Height of the device [m]
I	Current [A]
k_{spring}	Mechanical spring stiffness [N/m]
L	Length of the device [m]
m	Mass [kg]
m_a	Added mass [kg]
$P_{electrical}$	Power [W]
P_{wave_avg}	Average power per unit crest length [W/m]
P_{losses}	Power losses [W]
R	Resistance [Ω]
R_i	Internal resistance [Ω]
s	Scaling ratio [-]
S_ζ	Wave amplitude spectrum [m²s]
S_z	Heave response spectrum [m²s]
t	Time [s]
T	Wave period [s]
T_p	Peak wave period [s]
T_z	Zero crossing period [s]

V	Voltage [V]
W	Width of the device[m]
z_a	Heave amplitude [m]

Greek:

ζ	Surface elevation [m]
ζ_a	Wave amplitude [m]
λ	Wavelength [m]
ρ	Density [kg/m^3]
ω	Angular frequency [rad/s]
ω_0	Natural angular frequency [rad/s]
ω_p	Peak angular frequency [rad/s]

Contents

1 Introduction

Climate change and resource depletion have been the driving forces behind the developments in the renewable energy technologies. One of the technologies that has made big steps forward is wave energy. Wave energy has the potential to contribute a significant portion to the total electricity production of the world. In order to fulfill this potential further improvements are required. One of the many options for improvements is to optimize the wave energy converter (WEC) based on the sea state conditions it is operating in.

In this project a scale model of a WEC is built and experimental tests are performed in a wave flume. Additionally, a control system is researched and developed that is able to increase the power extraction of the WEC.

1.1 Background

The possibility for this project arose because of my MSc thesis, which I also wrote in Deltares. The MSc thesis was written on the following topic [1]:

„A Realistic Control System for a Wave Energy Converter for Optimum Power Production“

I my thesis I researched the different possibilites of how to improve the power extraction of a heaving point absorber type of WEC in irregular waves. In my work I proposed a realistic control system, that is able to improve the power extraction and subsequently the feasibility of the heaving point absorber type of WEC.

Point absorber: A point absorber is a floating device that is able to harness the energy from waves irrespective of the incoming wave direction. The floating device oscillates up and down (i.e. heaving motion) due to the motion of the wave and this oscillation is used to generate electricity. An example of a point absorber is depicted in Figure 1.

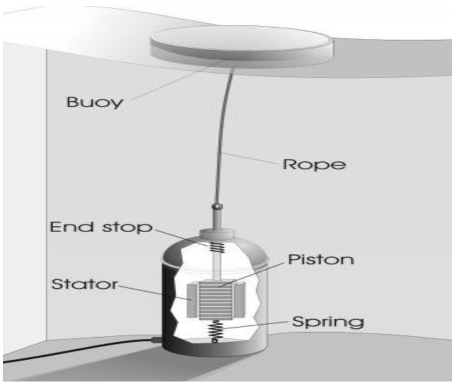

Figure 1 Point absorber

Optimum conditions: One of the characteristics of a point absorber is that under specific conditions a maximum amount of energy can be extracted and converted to electricity.

There are two optimum conditions that must be satisfied simultaneously and they are associated with the physical parameters of the point absorber. These conditions are different for regular waves and irregular waves:

In regular waves the first condition states that the natural angular frequency of the point absorber must be equal to the frequency of the incident wave. The second condition deals with the properties of the generator and states that the mechanical damping coefficient, associated with the generator, must be set to a value so that the destructive interference between the incoming and reradiated wave is largest.

In irregular waves the two optimum conditions have to be determined with numerical experiments. For each sea state the power extraction has to be determined numerically for all the possible combinations of natural angular frequency and the generator's damping. The experiment will result in optimum values for the natural frequency and the damping, when the power extraction is largest.

In my thesis I concluded that it is better and a more practical solution to tune the device based on the sea state. However, it should be noted that in theory it is also possible to tune the device to each incoming wave.

Control system: The previously discussed optimum conditions are different for each sea state. Seas and oceans are constantly changing and consequently the optimum conditions are constantly changing. This reasoning has led to the design of a control system. A control system is a set of devices that identifies the optimum conditions in real time and implements these conditions in pursuance of maximum power production. The control system will achieve its goal by taking the following steps in an automated fashion:

1) The motion of the point absorber in waves is recorded
2) The sea state is determined from the motion of the point absorber
3) Optimum conditions based on the sea state are calculated
4) Optimum conditions are applied
5) Steps 1-5 are repeated

1.2 Goals

During the first week, the goal of the internship was set in place. These goals were discussed and agreed together with my supervisor at Deltares, Dr. Ir. P. Wellens, and with my supervisor from the University of Twente, Dr. Ir. P. C. Roos.

The goal of the internship is take the role of a team leader. As a team leader I am responsible for managing the project, day-to-day activities and the project budget. The project is to build and test a scale model of a point absorber with a control system.

1.3 Methodology

It is necessary to choose the dimensions for the scale model point absorber. The wave flume, where the experimental tests will be performed, will serve as a bottleneck for the dimensions. Based on this the width, height and length of the will be decided. It is decided to make the width of the point absorber as wide as the wave flume itself to have only 2 dimensional waves.

The dimensions proposed in my MSc thesis will be used to make a scaled down version of the point absorber. Froude scaling laws will be used for scaling some of the dimensions of the point absorber and the sea states.

In order to choose a generator with adjustable damping and a spring with adjustable stiffness, different options are researched. Decisions are made based on the cost, suitability and availability of the devices. Additionally, team members are consulted who have in depth knowledge in these fields.

Experimental tests are performed to analyse the designed point absorber, spring system, generator and the control system. Tests are performed in the Deltares Scheldt Wave Flume.

In the interest of finishing the project in time, a work plan is devised. Additionally, the costs of the project are monitored closely to make sure the project stays within the budget.

1.4 Work Plan

Time	*Assignment*
12.06 – 18.06 (1 week)	Project preparation, background, goals.
19.06 – 02.07 (2 weeks)	Researching devices for control system (adjustable mechanical spring, generator with adjustable damping).
03.07 – 23.07 (3 weeks)	Designing the point absorber, mechanical spring, generator setup and the wave flume setup
24.07 – 06.08 (2 weeks)	Detailed drawings of all the parts. Production and orderding of the parts.
07.08 – 15.08 (1 week)	Installing the setup in a dry environment. Initial testing of the setup.
18.08 – 22.08 (1 week)	Making adjustments to the setup and preparing for tests in the wave flume.
25.08 – 29.08 (1 week)	Experimental tests in the wave flume.
01.09 – 05.09 (1 week)	Analysing the results, writing a report.

1.5 Team

A number of people have been involved in the project. The help and ideas received from the team members was a crucial factor to the success of this project. I would like to thank the following team members:

Peter Wellens, Jos Ooms, Goof Leendertse, Wim Taal, Rob Hoffman, Job Waaijerink and Pieter Pasterkamp.

2 Scale Model

In this chapter an overview is given of the experimental setup in the wave flume. The dimensions of the scale model point absorber are chosen, the design of the spring system and the generator is proposed. A device is introduced that is able to determine and record the displacements of the point absorber. And lastly the control system is discussed.

2.1 Experimental setup

The point absorber will be tested in the Deltares Scheldt Wave Flume. The setup will include a heaving point absorber, a fixed bed structure to hold the point absorber in place, spring system, generator and a system to measure the displacement of the device. The total setup is depicted in the Figure 2 below:

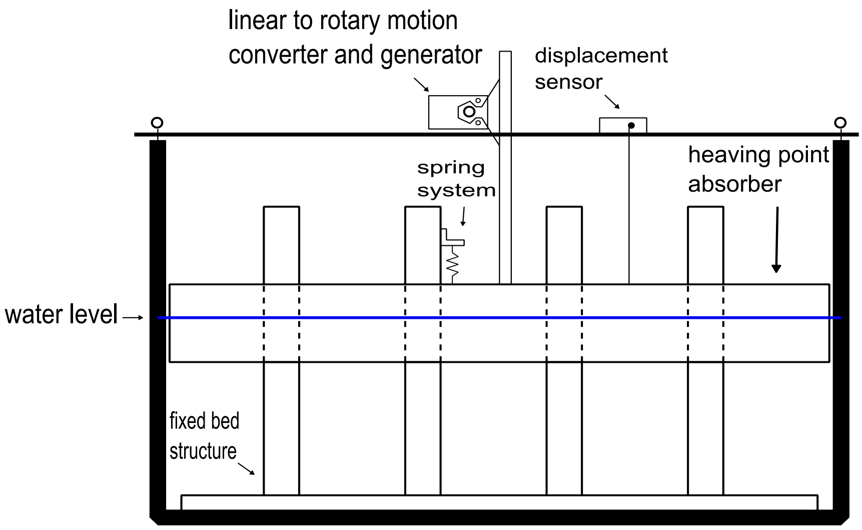

Figure 2 Experimental setup. Front view

The figure can be understood as standing at one end of the flume and looking to the other end of the flume. The water level in the flume will be 0.6 m. Fixed bed structure consists of four fixed poles along which the point absorber structure is oscillating. The fixed poles will hold the point absorber in place and will only allow 1 degree of motion – heave motion. The heaving point absorber is rectangular cuboid, having almost the same width as the flume itself. The spring system is used to add stiffness to the system with mechanical springs. The displacement sensor is a device that measures and records the displacements of the device. This information is necessary for the control system and power calculations. Last but not least, a system is used to convert the linear motion to rotary motion. The reason for this is that is much easier and less costly to obtain a rotational generator rather than a linear one.

2.2 Point Absorber Structure

The point absorber proposed in my MSc thesis has the shape of a cylinder. An oscillating cylinder in a wave flume will create 3 dimensional waves, which is not desired. The 3 dimensional waves will reflect back from the sides of the flume and affect the motion of the point absorber. Due to this it is decided to choose a different shape for the point absorber.

The point absorber is designed with a shape of a rectangular cuboid (see Figure 4), having almost the same width as the wave flume. The wave flume is 100 cm wide. If the width of the point absorber is the same as the width of the flume, only 2 dimensional waves occur as depicted in Figure 3.

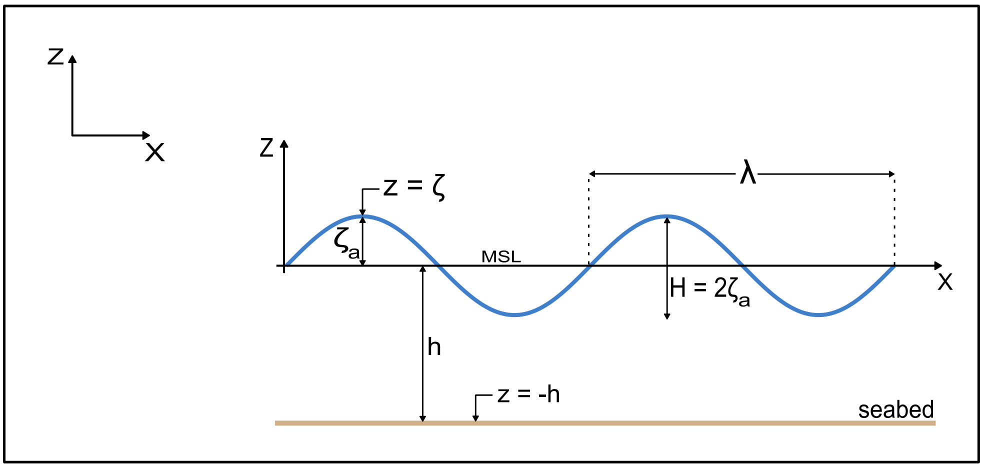

Figure 3 Schematization of major symbols and axes of direction

It is decided to use a scaling ratio of 1:45. It should be noted that not all parameters can be scaled down in a straightforward way because the full scale point absorber is a cylinder, but the scale model is a rectangular cuboid. The below tables list the parameters of the full scale point absorber from my MSc thesis and the scale model:

Table 1 Parameters of the full scale point absorber and the scale model

Full scale point absorber	
Radius [m]	10
Draft [m]	6
m [kg]	1932000
m_a [kg]	2146800
Restoring spring coefficient c [N/m]	3158900
Natural frequency ω_0 [rad/s]	0.88

Scale model	
Draft [cm]	11
W - Width [cm]	98.5
L - Length [cm]	19.8
H_{height} - Height [cm]	20
m [kg]	21.2
m_a [kg]	30.9
Restoring spring coefficient c [N/m]	1913.2
Natural frequency ω_0 [rad/s]	6.06

The scaling laws and formulas are discussed in Appendix A. Additionally the calculations of the added mass, restoring spring coefficient, draft and the natural frequency for the scale model are provided in Appendix A.

The final design of the point absorber structure is shown in Figure 4.

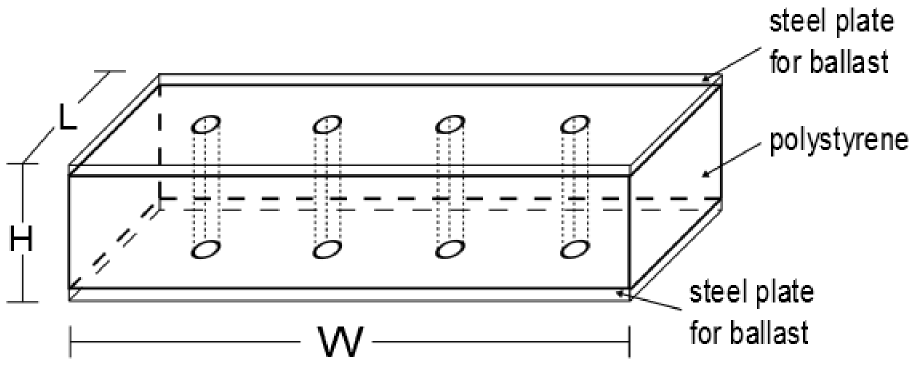

Figure 4 Point absorber design

The middle part of the structure is made of polystyrene, which is a very low density material. In order to achieve the required mass of the scale model (21.2 kg), two stainless steel plates are added on both sides of the polystyrene. The structure will have 4 holes in the middle to be able to place the point absorber over the four fixed poles.

2.3 Spring System

A spring system must be present that is able to adjust the stiffness of the system. Changing the stiffness of the system changes the natural frequency of the system. In my thesis I proposed a gas spring system, in which the gas pressure inside a cylinder can be increased to increase the stiffness. After doing some research, I found a company that is able to provide an adjustable gas spring system. The company is called Safelink and they provide engineering solutions for offshore lifting operations [2]. Unfortunately the cost of the gas spring system was too high.

As a less costly alternative it was decided to use a mechanical spring. It should be noted that this will be a passive spring system. Installing a simple mechanical spring means that during the test it is not possible to adjust the stiffness. In order to change the stiffness, the test needs to be stopped and the spring needs to be added to or removed from the system

A mechanical spring was purchased from Alcomex [3], whose stiffness is listed in Table 2. Additionally, the natural frequency of the point absorber when using the spring is listed in Table 2.

Table 2 Mechanical spring properties

	k_{spring} [N/m]	ω_0 [rad/s]
Spring	270	6.47

Thus it is possible to increase the natural frequency from 6.06 rad/s (without mechanical spring) to 6.47 rad/s with the spring. The designed spring system is depicted in Figure 5 below:

Figure 5 Mechanical spring system

In Figure 5 the red bracket is fixed to the pole. The spring is fixed to the bottom and to the red bracket. As the device oscillated up and down, the spring compressed and decompresses. The metal rod, which moves through the red bracket, holds the spring in a correct vertical position.

2.4 Displacement Sensor

A displacement sensor is used to measure and record all the motions of the point absorber in waves. This information is necessary for the principle operation of the control system described in paragraph 1.1. From the motion of the point absorber it is possible to determine the sea state and the optimum conditions for that sea state. The displacement sensor is shown in Figure 6.

Figure 6 Displacement sensor

The displacement sensor is fixed to a stationary platform. From the displacement sensor comes out a wire which is connected to a metal plate, which in turn is connected to a metal rod. The metal rod is connected to the point absorber structure and it oscillated together with the device. As the metal rod moves up, more wire comes out of the displacement sensor and as the metal rod goes down, wire goes back into the displacement sensor.

The displacement sensor is actually a potentiometer, which in other words is a variable resistor. As wire is being pulled or inserted back, the resistance in the displacement sensor changes, which then changes also the voltage from the sensor. Measuring the voltage it is possible to convert it to amplitudes in cm for example. This is done with Deltares in-house software called "Delft Measure".

2.5 Generator

To extract energy from the waves a generator is required. Different type of generators were researched and tested. In the end a Shimano 6V 2.4W dynamo was chosen as the generator. The dynamo is depicted in Figure 7.

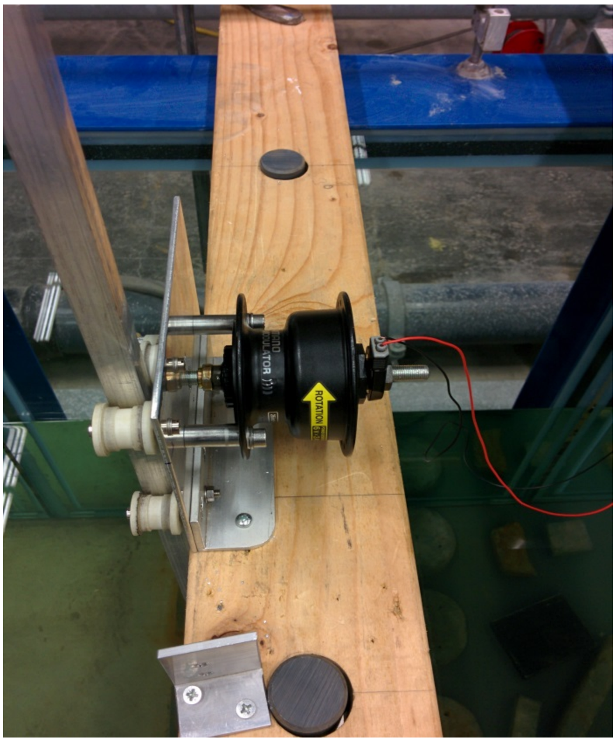

Figure 7 Shimano dynamo used as a generator

This is a simple bicycle dynamo that can be purchased from a bicycle shop. The dynamo works on the rotational principle. Thus in order to drive the dynamo, the linear motion of the point absorber must be converted to rotational motion. This is achieved by using an omega drive as shown in Figure 8.

Figure 8 Omega drive to convert linear motion to rotational motion

In Figure 8 the metal rod is fixed to the point absorber and oscillates up and down in waves. A belt is used to drive the pinion (the round gear), which is connected to the shaft of the dynamo.

In order to get electrical energy from the dynamo it needs to be connected to a load. A load can be a resistor (or a light bulb as on a bicycle) connected in series with the dynamo. The dynamo will generate voltage which flows across the resistor. Measuring the voltage over the resistor is enough information to calculate the electrical power generated by the dynamo. The electrical circuit of the system is illustrated in Figure 9.

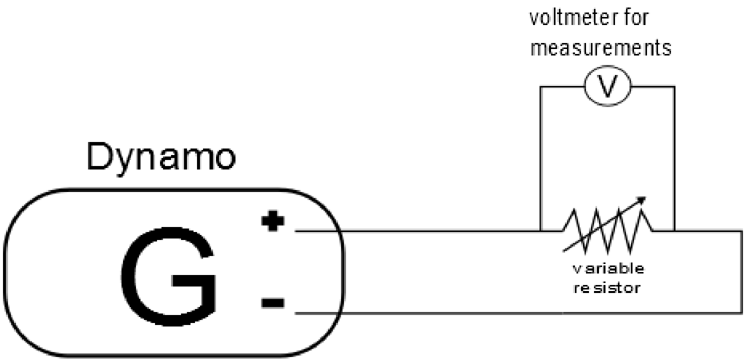

Figure 9 Electrical circuit of the system

The voltage measurements are recorded again with "Delft Measure" software. The electrical power produced by the dynamo is calculated by:

$$P_{electrical} = \frac{V^2}{R} \qquad 1.1$$

With:

V - Voltage [V]
R - Resistance [Ω]
$P_{electrical}$ - Power [W]

2.5.1 Mechanical Damping Coefficient

In paragraph 1.1 it was explained that the second optimum condition is associated with the mechanical damping coefficient. Mechanical damping coefficient determines how much damping (i.e. resistance) is provided to the rotational movement of the dynamo. In this setup the damping is provided by the resistor depicted in Figure 9.

For every sea state there is an optimum value for the amount of damping required to yield in maximum power production. Considering this, it is necessary to have a variable resistor whose resistance value can be adjusted. The variable resistor used in this setup is shown in Figure 10.

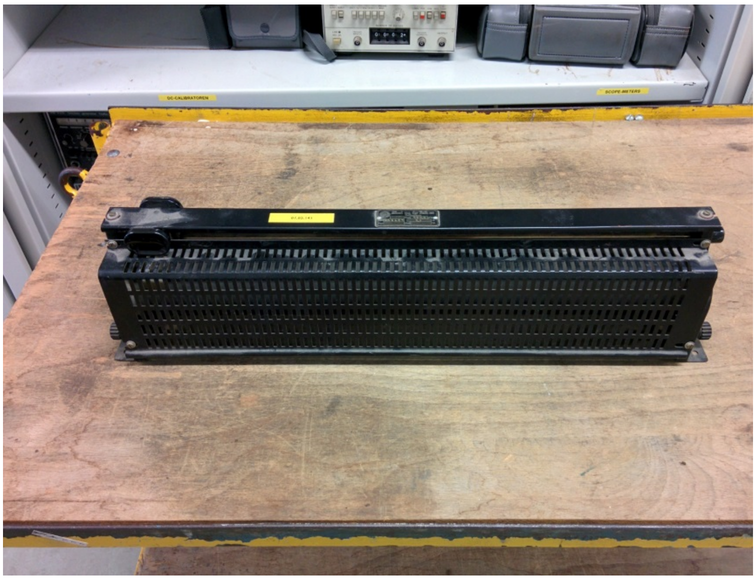

Figure 10 Variable resistor

The resistance can be varied from 0 to 90 Ω. It should be noted that the resistance has to be adjusted manually, just like the spring stiffness. In reality it is also possible to purchase or design a digital variable resistor, which can be adjusted in an automated fashion.

The mechanical damping is a function of the resistance. The damping increases when the resistance is decreased and the other way around. This can be understood by looking at the Ohm's law and Lenz's law. Ohm's law can be described mathematically by the following formula:

$$I = \frac{V}{R} \quad 1.2$$

In which I is the current in Amps. When decreasing the resistance, the current increases. This current creates a magnetic field which opposes the force that produced the current in the first place (Lenz's law). The more current there is the more opposing force is applied to rotational movement of the dynamo.

2.6 Control System

In paragraph 1.1 the working principle and the advantage of having a control system was explained. Now all the necessary devices for the control system have been designed or researched:

- There is a displacement sensor that is able to record the motion of the point absorber and from that information it is possible to determine the sea state, which is explained in more detail in my MSc thesis.
- There is a possibility to have an adjustable gas spring system. However, due to the cost, we are restricting ourselves to manually changeable springs.

- It is possible to change the damping of the dynamo by adjusting the resistance of the circuit. However, due to time constraints we have to restrict us again to a manually changeable resistor device.

Unfortunately, it is not possible to design the control system that works in automated fashion, since we will be using manually changeable spring system and damping. However, if one has a gas spring system and a digital variable resistor, the only thing required is a controller unit and a suitable algorithm for the controller. The algorithm would determine the sea state from the motion of the point absorber and would then calculate the corresponding optimum conditions for that sea state – the required pressure in the gas spring system and the required resistance value for the digital resistor. One option would be to use the algorithm developed in my MSc thesis.

3 Experimental Tests

In this chapter the wave conditions for the experimental tests are introduced. Experimental tests are performed and the results of the tests are shown and analyzed. The first tests are performed in regular waves for determining the RAO of the point absorber. The other tests are performed in irregular waves to determine the optimum damping for a sea state.

3.1 Experimental Setup in the Wave Tank

All the structures and devices introduced in Chapter 2 were installed to the Eastern Scheldt Wave Flume. Water level was set to 0.6 m. The experimental setup is illustrated in Figure 11:

Figure 11 Experimental setup in the wave flume

The point absorber floated with 11 cm draft as was expected from the calculations in Appendix A. There was some friction between the poles and the point absorber, but it was not significant and still allowed the device to move quite freely. The width of the device, which was 98.5 cm, seemed to be a good choice. The flume itself is 100 cm and there was just enough room, so the device would not touch the side of the flume.

3.2 Determining the Response Amplitude Operator

The goal of the first experimental tests is to determine the RAO of the point absorber. This enables to check if the calculated natural frequency and experimental tests agree. It also gives a good understanding of the point absorbers behaviour in different waves. The RAO is determined for two different cases:

1) Without a mechanical spring

2) With a mechanical spring

Without the mechanical spring the natural frequency of the device should equal to:

$$\omega_0 = \sqrt{\frac{c + k_{spring}}{m + m_a}} = \sqrt{\frac{1913.2 + 0}{21.2 + 30.9}} = 6.06 \text{ rad/s} \qquad 1.3$$

And with the mechanical spring installed, the natural frequency should equal to:

$$\omega_0 = \sqrt{\frac{c + k_{spring}}{m + m_a}} = \sqrt{\frac{1913.2 + 270}{21.2 + 30.9}} = 6.47 \text{ rad/s} \qquad 1.4$$

In order to check if this is true, the point absorber with and without spring is tested in a number of regular waves. The response of the point absorber should be largest at its natural frequency as in eq. 1.3 and 1.4. A scaling ratio of 1:45 was used to scale down some of the parameters of the point absorber and thus the same ratio is used to calculate the wave parameters. Scaling relationships for wave parameters are provided in Appendix A. Table 3 lists the wave height, wave period, duration and their scaled-down equivalents:

Table 3 Regular waves for determining the RAO

	Original value		**Scale model value**		
Test number	T [s]	H [m]	T [s]	H [m]	Duration [s]
1	4.7	1.8	0.7	0.04	60
2	5.4	1.8	0.8	0.04	60
3	6.0	1.8	0.9	0.04	60
4	6.4	1.8	0.95	0.04	60
5	6.7	2.3	1	0.05	60
6	6.9	2.3	1.03	0.05	60
7	7.0	2.3	1.05	0.05	60
8	7.4	2.3	1.1	0.05	60
9	8.0	2.7	1.2	0.06	60
10	9.4	2.7	1.4	0.06	60
11	10.7	2.7	1.6	0.06	60
12	12.1	2.7	1.8	0.06	60
13	13.4	2.7	2	0.06	60

Experimental tests were performed for all the regular waves listed in the table above. The response of the point absorber, recorded with the displacement sensor, can be used to determine the RAO for both setups. Figure 12 below shows the RAO for both setups, one without a spring and the other with a spring:

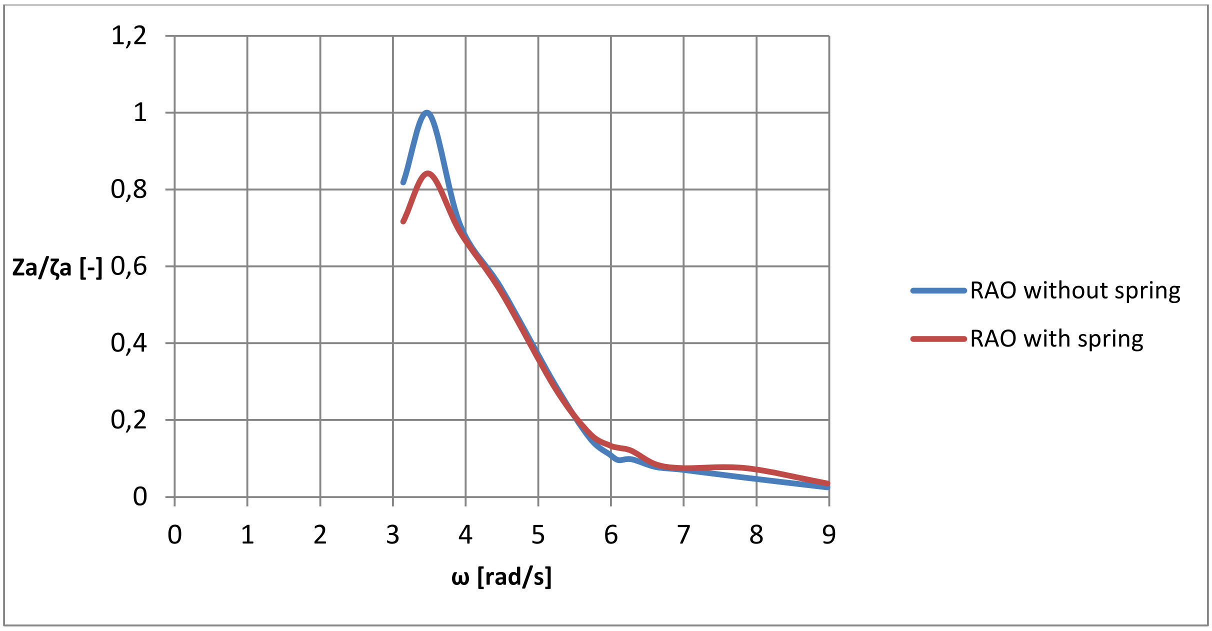

Figure 12 RAO with and without spring

In Figure 12 the natural frequency is not visible from the results. In theory the largest response should occur around 6.06 rad/s and 6.47 rad/s. The results seem to agree with other expectations, that with high frequency waves (ω > 7 rad/s) the response tends to zero and with low frequency waves the response tends to 1.

One of the explanations to the poor RAO results is that the higher frequency waves are too short for the device. If the wavelength is very short compared to the length of the device, the pressure distribution is not uniform under the device. This means that the device does not want to move in the heave motion but also in the rolling motion as illustrated in Figure 13.

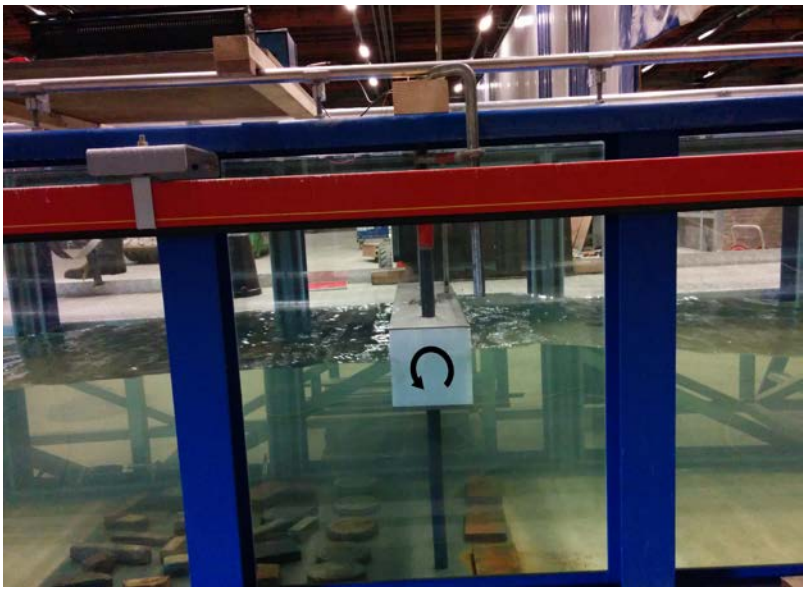

Figure 13 Rolling motion due illustration

The rolling motion increases the friction between the poles and the point absorber. The friction can become large enough so that the vertical motion is significantly reduced.

Due to the poor response in shorter waves, there is no use for the mechanical spring to increase the natural frequency. As a result of this all the other tests will be performed without the mechanical spring and in wave climates with longer waves.

Media files:

Here is a video example of the device in shorter regular waves, where the device experiences the previously discussed rolling motion:

https://dl.dropboxusercontent.com/u/47965009/short%20waves.mp4

And a comparison scenario with longer regular waves, where the rolling motion is much smaller:

https://dl.dropboxusercontent.com/u/47965009/longer%20waves.mp4

3.3 Determining the Optimum Damping for Maximum Power Extraction

The goal of this experiment is to determine the optimum value for the damping (resistance) in a sea state (in irregular waves). It was explained earlier in paragraph 2.5.1 that the damping of the dynamo can be adjusted by changing the resistor value of the circuit. Thus what we are actually looking for is the optimum value for the resistance. This will be achieved by doing a number of tests in the same sea state but with a different resistance value. The power extraction for each scenario will be calculated and compared.

It is decided to test the point absorber with different resistor values in two sea states. Due to the poor performance in shorter waves, which came obvious in paragraph 3.2, it is decided to choose sea states with larger peak periods. Each sea state will be repeated five times, each time with a different resistor value. To provide a good statistical analysis, the sea state should be comprised of at least 1000 waves. To calculate the total duration of the sea state, the zero crossing period, T_z, is multiplied by 1000. Zero crossing period is defined as the mean period of all the waves in the wave record. The relationship between the peak wave period and zero crossing period is the following [4]:

$$T_p = 1.4T_z \qquad 1.5$$

In the below Table 4 are shown the sea state parameters and the resistor values for the experiments.

Table 4 Sea state parameters for determining the optimum damping value

	Original value		Scale model value				
	T_P [s]	H_s [m]	T_P [s]	H_s [m]	T_z [s]	Duration [s]	Resistance values to be tested [Ω]
Sea State 1	8.5	3.2	1.27	0.07	0.91	910	10,30,50,70,90
Sea State 2	12.1	4.1	1.8	0.09	1.29	1290	10,30,50,70,90

Both sea states were repeated 5 times, each time with a different resistor value and the average power extraction for each scenario is presented in Figure 14.

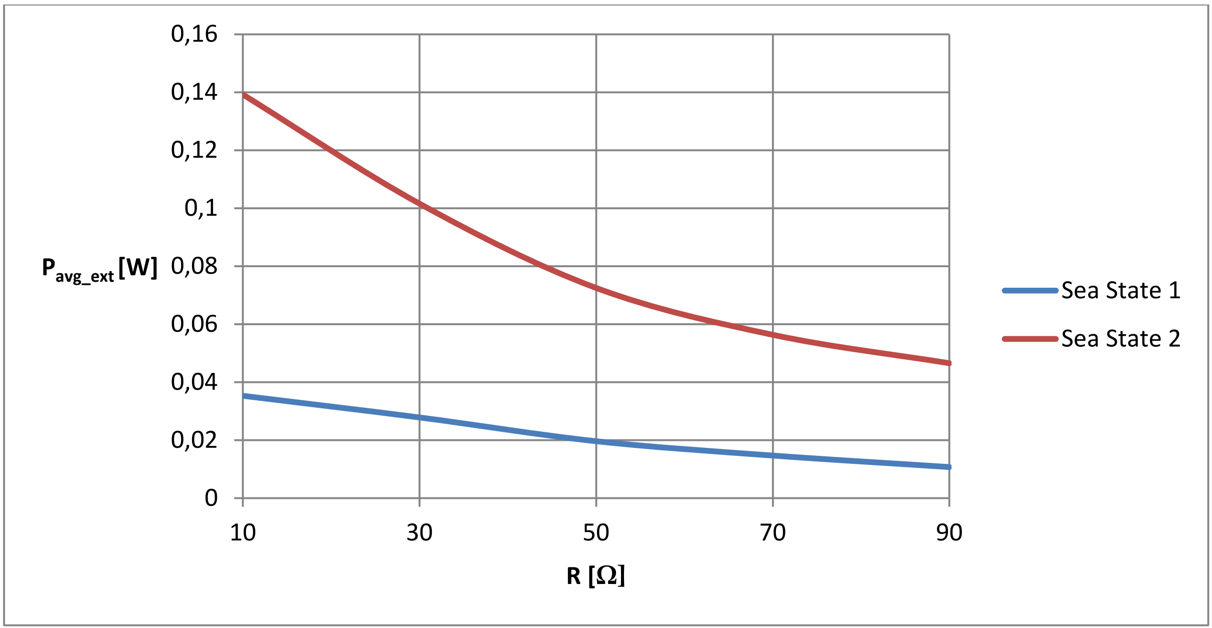

Figure 14 Average power extraction for different resistor values

As expected, the average power extraction decreases as resistor values get higher. With large R values, the damping is decreased, which is not the optimum for the tested sea states. Both sea states have a very large peak period and thus require more damping to extract more energy.

For both sea states the maximum average power extraction occurs when $R = 10\ \Omega$. However, in these experiments we did not find the optimum resistor value for the sea state – because it is highly likely that the when decreasing R value close to 0, the average power extraction will peak at one point and the decrease. The peak point is what we are looking for. Before doing the experiments it was expected that the peak point will occur somewhere between $R = 10\ \Omega$ and $R = 90\ \Omega$ and due to this the point absorber was never tested with lower R values.

It is also possible that for this dynamo and these sea states the optimum power peak will not occur even when $R < 10\ \Omega$. This means that this dynamo is not powerful enough to provide enough damping for this type of sea state. Thus when choosing a generator for a WEC, the designer should keep in mind that the generator should be able to provide enough damping for the wave climates it will be operating in.

Another characteristic property of a dynamo is its internal resistance R_i, illustrated in Figure 15. Just like the variable resistor in our circuit, the dynamo's internal resistance also dissipates voltage. This means that some of the power is lost to the internal resistance of the dynamo, which is not what we want. The internal resistance of a dynamo should be as small as possible, so more power can be extracted.

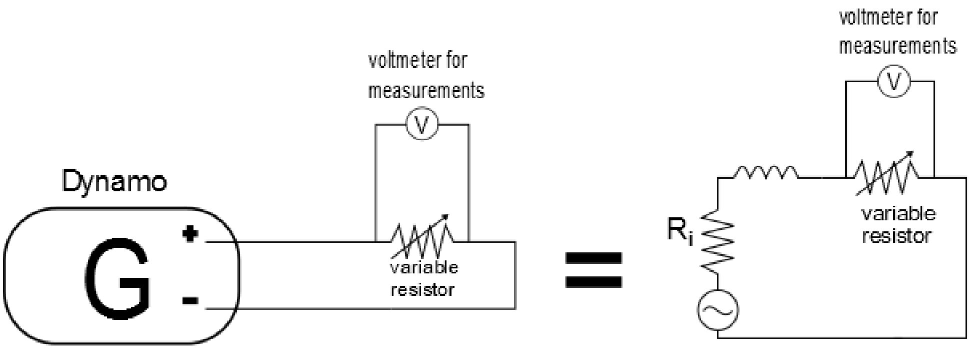

Figure 15 Dynamo circuit diagram

The internal resistance of the dynamo, measured with a multimeter, is $3.5\,\Omega$. Calculating the current, I, at the variable resistor, it is possible to calculate the power dissipated by the internal resistor with:

$$P_{losses} = I^2 R_i \qquad 1.6$$

Imagining a scenario where the internal resistance is very small ($R_i \leq 0.1\,\Omega$) the average power extraction from both sea states would result in the following values depicted in Figure 16 (this is just adding the power losses in dynamo to the power extraction values).

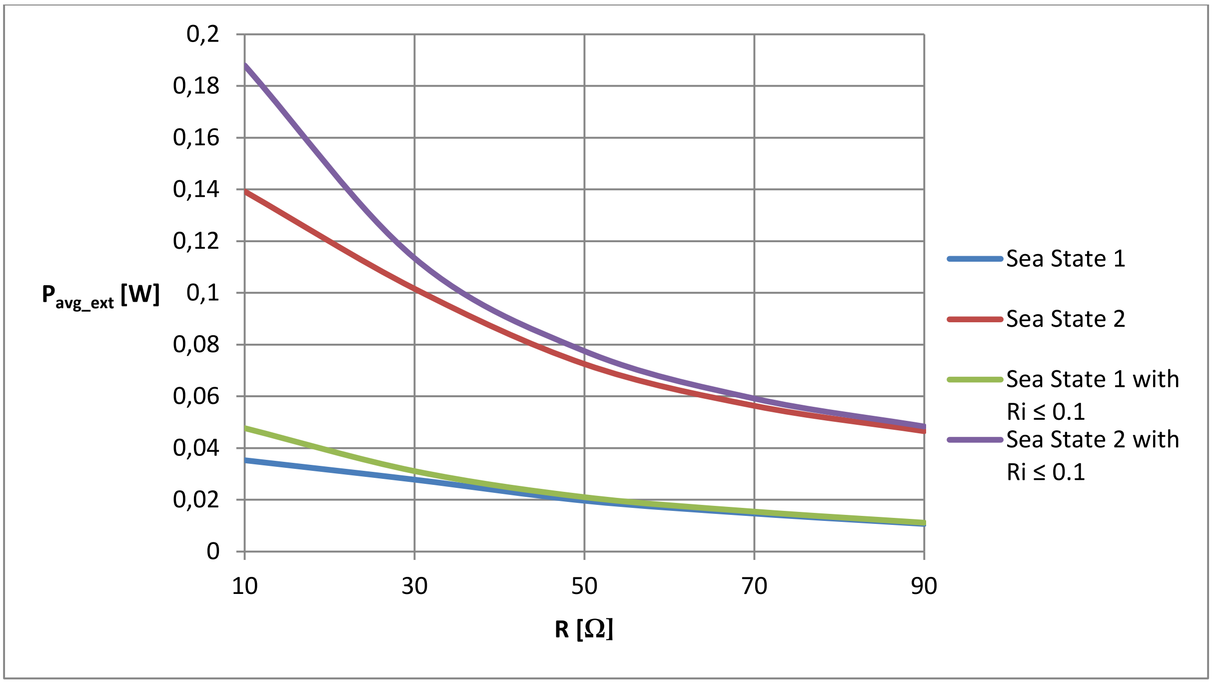

Figure 16 Average power extraction for different resistor values. Red and blue line represent the measured power. Green and purple line represent the calculated power when internal resistance is very small.

It is seen from Figure 16 that the average power extraction would be significantly increased (35% increase at $R = 10\ \Omega$) when choosing a dynamo with very low internal resistance. Thus the internal resistance is another critical aspect that should be taken into account when choosing a generator for a WEC.

Media files:

Side view of the device in irregular waves:

https://dl.dropboxusercontent.com/u/47965009/irregular%20waves%20side%20view.mp4

Front view of the device in irregular waves:

https://dl.dropboxusercontent.com/u/47965009/irregular%20waves%20front%20view.mp4

Lighting an LED with wave energy:

https://dl.dropboxusercontent.com/u/47965009/lighting%20and%20LED.mp4

Wave overtopping. This is not a desired effect:

https://dl.dropboxusercontent.com/u/47965009/wave%20overtopping.mp4

4 Summary, Conclusions and Recommendations

In this chapter an overview will be given of the work done and the results obtained during the internship. Additionally, recommendations will be given for further work and improvements.

4.1 Conclusion and Summary about Project Management

The goal of the internship was to take the role of a team leader. The project was to design and build a scale model of a point absorber with a control system. As a team leader I was responsible for managing the project, day-to-day activities and the project budget.

Overall the work plan that was set in place in the beginning of the internship was followed closely. I only underestimated the time it would take to communicate with companies, obtain information about their products and the delivery time of products. Many times they did not have a product in stock and it would take weeks to receive it. Also the internship period happened to be during the time when a lot of people were on holidays and this added additional complications to talking with the companies.

Communication with other team members was very good. The knowledge and skills of team members was more than sufficient. Just as a note, in the future it would be wiser to prepare better for meetings with other team members so more things can be covered during the meeting. The hour rate of consultation is quite expensive and it would save both time and money.

Project budget:

Table 5 Project budget

Working hours of team members [hrs]	45.7
Total cost of working hours [EUR]	3144
Cost of parts [EUR]	492
Total costs [EUR]	3636

4.2 Conclusion and Summary about the Project

A scaled-down model of a point absorber was designed and built. A scaling ratio of 1:45 was used. A mechanical spring system was designed that can be used to add stiffness and subsequently change the natural frequency of the system. This however, is not an automatic system where the stiffness could be adjusted in mid-operation. Instead the operation must be stopped and the spring should be changed manually for a different spring for example. As a side note, a company was found called Safelink that is able to build a gas spring system. This system would work in automated fashion and allows adjusting the stiffness in mid-operation. Unfortunately the price of the gas spring system was too high.

A bicycle dynamo was chosen as a generator for the point absorber. A dynamo is a good choice, since it is designed to work on low RPM's, which is also characteristic to wave energy generators. An electrical circuit was designed for adjusting the damping of the dynamo. The damping was adjusted by changing the resistance that is inserted into the circuit. The resistance was changed with a variable resistor. However, the resistance had to be changed manually, just like the mechanical spring. Research was done to find a system where the damping can be adjusted automatically. A solution would be to use a digital variable resistor that can be adjusted with a controller.

Unfortunately it was not possible to build a control system, because we were using a spring system and a damping system that have to be changed manually. However, alternatives that could be adjusted automatically were researched and proposed (gas spring system and digital variable resistor). If one has these systems, all that is needed is a controller and an algorithm that calculates the necessary conditions for the gas pressure and the digital resistor.

Experimental tests were performed in regular and irregular waves:

In regular waves the RAO of the device was determined. The device showed very poor response in shorter waves. Due to this also the natural frequency was not visible from the results. The poor response in short waves was mainly because the wavelength was too short for the length of the structure. Due to this the pressure distribution was not uniform under the structure, which resulted in a rolling motion and increased the friction between the poles and the point absorber.

In irregular waves it was shown that by adjusting the damping (resistance) of the dynamo the power extraction is increased. The point absorber with different resistor values was tested in two sea states. Results showed that for both sea states, the maximum average power production occurred when setting the resistor to the smallest tested resistor value ($R = 10\ \Omega$). The smaller the resistor value the more damping is provided by the dynamo. The tests were performed in stormy sea states and thus it was beneficial to have more damping to extract more power from waves. It is highly likely that the power production could have been further increased by setting the resistor to an even lower value. However, it was expected that the maximum peak will occur within the tested resistor values and no tests were performed with setting $R < 10\ \Omega$.

Additionally, it was shown that it is beneficial to have a generator with very low internal resistance. It was shown that by decreasing the internal resistance of the dynamo from 3.5 Ω to 0.1 Ω the average power extraction increases by 35%.

4.3 Recommendations and Further Work

- The next step in developing a point absorber with a control system would be to buy or build a gas spring system and use a digital variable resistor. Then it is necessary to design a controller with an adequate control algorithm. The algorithm should calculate the optimum conditions for the pressure inside the gas spring system and the resistance value for the digital resistor. An option for the algorithm is the one developed in MSc thesis.

- Currently, the damping of the dynamo is adjusted by changing the resistance of the circuit. However, in my MSc thesis the damping value is calculated in units of kg/s. Thus it is necessary to determine the relationship between the resistance and damping of a dynamo.

- The scale model of the point absorber should be designed with a lower natural frequency, without changing the dimensions too much. This way the natural frequency of the point absorber will be more visible.

- The friction between the poles and the point absorber should be decreased. This way the response of the scale model in shorter waves is improved. One option is to test a low friction bearing system.

5 Bibliography

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6 Appendices

6.1 Appendix A

Scaling laws

Scaling can be achieved with using the non-dimensional Froude number:

$$F_r \propto \frac{U}{\sqrt{gl}} \propto \frac{F_i}{F_g} \qquad 1.7$$

With:

$$\begin{aligned} F_i &= \rho U^2 l^2 \\ F_g &= \rho g l^3 \end{aligned} \qquad 1.8$$

In which:

U - Fluid velocity
g - gravitational acceleration
l - Length characterizing fluid/solid interaction
F_i - Intertia force
F_g - Gravitational force

Defining s as the scale between full-scale and scale model conditions, the following scaling ratios for the point absorber parameters are derived [5]:

Table 6 Froude scaling laws

Quantity	Scaling
Wave height and length	s
Wave period	$s^{0.5}$
Power density (power per unit length)	$s^{2.5}$
Mass	s^{3}
Force	s^{3}
Torque	s^{4}
Power	$s^{3.5}$
Linear stiffness	s^{2}
Linear damping	$s^{2.5}$

Added mass

The added mass is calculated for a cylinder shaped object. The formula for the added mass is [6]:

$$m_a = \rho_w \pi Radius^2 W \qquad 1.9$$

In which:

ρ_w - Density of water [kg/m3]
Radius [m]
W - Width of the cylinder [m]

This formula is valid for a cylinder, however it can be used to give an approximation of the added mass for a rectangular cuboid. Using a radius of 0.1 m and width of 0.98 m from Table 1, the added mass is calculated:

$$m_a = 1000\frac{kg}{m^3}\cdot\pi\cdot\left(0.1m\right)^2\cdot 0.985m = 30.9 \text{ kg} \qquad 1.10$$

Restoring spring coefficient

The restoring spring coefficient, c, is calculated as follows:

$$c = \rho_w gWL \qquad 1.11$$

With L the length and W the width of the rectangular cuboid in meters, the restoring spring coefficient yields:

$$c = 1000\frac{kg}{m^3}\cdot 9.81\frac{m}{s^2}\cdot 0.985m\cdot 0.198m = 1913.2 \text{ N/m} \qquad 1.12$$

Draft

In order to make sure that the scale model will float with a certain draft, the buoyancy force, F_b, and the gravity force, F_g, are calculated. For the device to float at a certain draft:

$$F_b \geq F_g$$

$$F_b = \rho_w gV_{submerged} = \rho_w g\cdot W\cdot L\cdot Draft = 1000\frac{kg}{m^3}\cdot 9.81\frac{m}{s^2}\cdot 0.985m\cdot 0.198m\cdot 0.11m = 210.5 \text{ N} \qquad 1.13$$

$$F_g = mg = 21.2kg\cdot 9.81\frac{m}{s^2} = 208 \text{ N} \qquad 1.14$$

Thus the scale model will float with submerged draft of approximately 0.11 m.

Natural frequency

The undamped natural frequency of the system is calculated by:

$$\omega_0 = \sqrt{\frac{c}{m+m_a}} \qquad 1.15$$