Experimental Study on the WavePiston Wave Energy Converter

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AALBORG UNIVERSITY
Department of Civil Engineering

DCE Contract Report No. 73

Aalborg University
Department of Civil Engineering
Wave Energy Research Group

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by

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Preface

This report presents the results of an experimental study of the power performance of the WavePiston wave energy converter. It focuses mainly on evaluating the power generating capabilities of the device and the effect of the following issues:

- Scaling ratios
- PTO loading
- Wave height and wave period dependency
- Oblique incoming waves
- Distance between plates

During the study, the model supplied by the client, WavePiston, has been rigorously tested as all the anticipated tests have been done thoroughly and during all tests, good quality data has been obtained from all the sensors.

The client participated at all the tests performed on the model in the laboratory, and was then represented by Kristian Glejbøl and Martin von Bülow.

The laboratory tests were performed by Arthur Pecher and Elisa Angelelli under the supervision of Jens Peter Kofoed in February, 2010. This report has been prepared by Arthur Pecher and Jens Peter Kofoed. Contact regarding this work can be made to Jens Peter Kofoed, jpk@civil.aau.dk, +45 9940 8474.

Aalborg, April, 2010

Version	Date	Author	Comments
0.1	24.03.2010	AFSP	First draft
0.2	31.03.2010	AFSP, JPK	Second draft, submitted to client
1.0	17.04.2010	AFSP	Final report, reviewed by JPK, Elisa and Kristian Glejbøl

Contents

1. Introduction

The WavePiston wave energy converter was first conceived in 2008 and is currently being developed by a team including Kristian Glejbøl and Martin von Bülow of WavePiston, Denmark. The WavePiston WEC is more specifically known as an oscillating wave surge converter, as it extracts the kinetic energy available in the orbitally moving water particles, due to the interaction with the waves, through a number of translating moving plates positioned just underneath the water surface. This device is unique from the rest of the oscillating wave surge converters due to it having one moored reference frame supporting a multitude of working plates that are placed in parallel and in line relative to the incoming wave. In opposite to other wave energy converters from the same type, the plates are translating in the direction of the waves rather that rotating around an axle parallel to the waves. In principle, the multiple plates can be integrated in the same structure and share a PTO system, which should reduce the total needed installation, the mooring systems and so the total amount of material per installed kW. Moreover, the multiple plates will help to minimize the force on the mooring system, while the plates should complement each other to extract the maximum amount of energy.

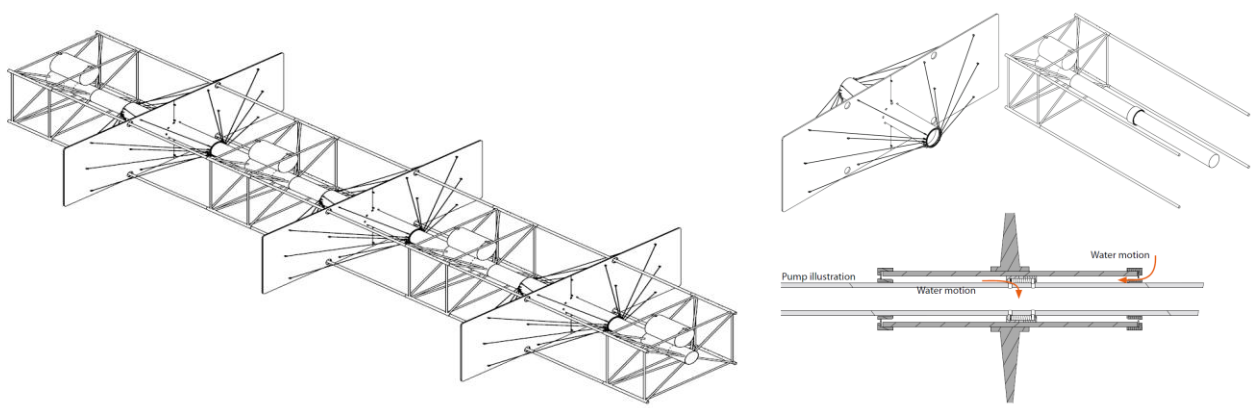


Figure 1: Artist impression of the envisaged WavePiston system.

In figure 1, some parts of the envisaged full-scale WavePiston wave energy converter can be seen, which consists of the following components:

- Vertical plates acting as independent pumps.
- A flexible pipe in the middle, which is the main part of the structure and transports the pressurized seawater to the turbine station.
- A spring system that move the plates back to their reference position.
- A mooring system for the whole structure.
- A turbine station that would convert the pressurized seawater into electricity, which could be shared with other similar structures.

For testing purposes the structure and power take off (PTO) unit is modelled in a different way (Fig.2) compared to how it will be designed in full-scale. The plates are individually connected to a PTO system, which includes an adaptable load system. The adaptable load system consists of a rail on which weights were applied, from 1 to 3 kg, in order to change the friction. On 2 of the plates, the displacement of the plates and the corresponding transferred force from the waves to the plates are measured through force transducers and a linear displacement sensor. The reason that only two plates have force measurements is due to the limited availability of force transducers and displacement sensors at the time.

The aim of the experiments is to investigate the power generating capabilities of the device, as well as to analyze some of the main influential parameters of the device, such as oblique waves and the effect of the distance between the plates. Oblique waves and short inter-plate distances are expected to decrease the performance of the device, due to a reduction in surface area of the plates that is exposed to the waves, or due to the loss of energy in the wave, as they do not have the required space to reform completely in between the plates. The report also aims to examine other key design parameters, such as the dependency of the device to the wave period and wave height, and to identify the optimal load and scaling ratio.

2. Test Setup

The data acquisition was done at a sampling rate of 20Hz for the wave gauges and 10Hz for the PTO system. The testing basin had a water depth of 0.7 m and the model was first anticipated to be designed as a 1:20 scale but in the early testing stage this was adapted to a 1:30 scale device, and so the testing parameters (Hs and Tp) were changed correspondingly.

Several instruments were mounted on and around the model in order to obtain the desired measurements. The instrumentation consisted of:

- 4 wave gauges (WG), which were located in line with the model.
- 2 linear displacement sensors, connected to the support of the plates, to record the movement of the plates.
- 2 force transducers, placed in between the displacement sensors and the support of the plates of the front and rear plate.
- When more than 2 plates were mounted, they were set at the same load as the instrumented plates but their performance was not recorded.

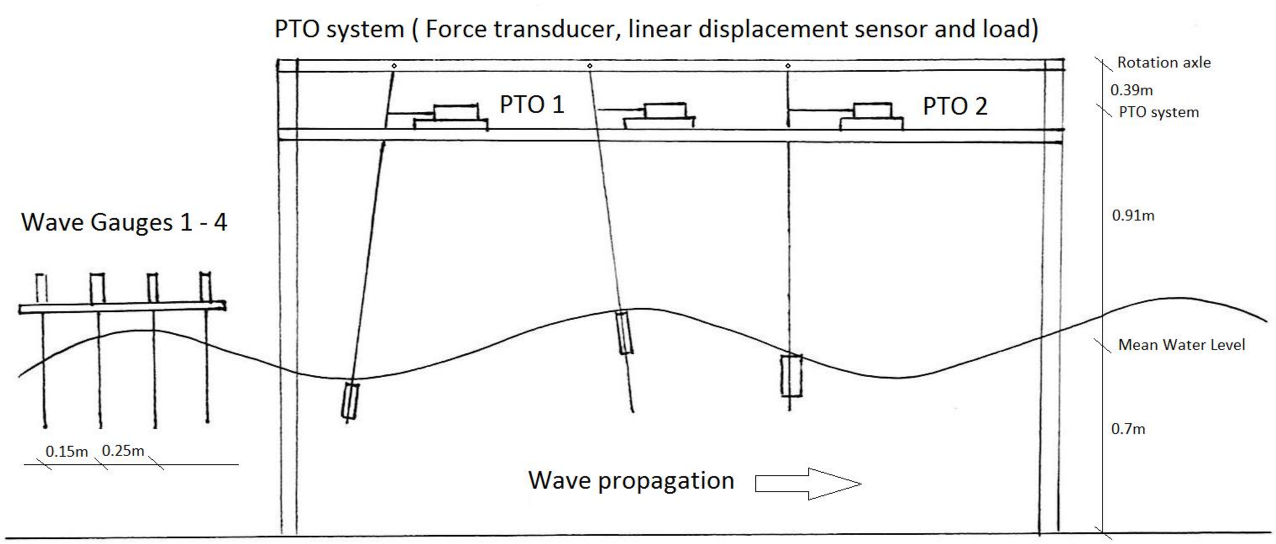


Figure 2: Test and instrumentation setup of the WavePiston 1:30 scale model

The wave gauges were positioned in order to obtain the most accurate representation of the waves. Therefore, four wave gauges were mounted in front and in line with the centre line of the model. The corresponding wave characteristics, the significant wave height (Hs), the wave peak period (Tp) and the power per meter of incoming wave (Pw), were calculated based on the reflection analysis of the 3 front gauges and the water depth by the software Wavelab 3.34, developed at the Department of Civil Engineering at Aalborg University.

The full-scale device will be completely submerged, have some flexible mooring system, have numerous plates integrated in a common flexible structure and all the plates will be connected to a common PTO system. On the other hand, the lab model consists of a fixed structure that is located out of the water and individual PTO systems for every plate. In order to make the two setups as comparable as possible, the pivot point of the plates was high above the surface of the water, minimising the rotation angle, and the plates were allowed to move vertically, to mimic the flexibility of the centre tube in the real system. The change in setup is related to the difficulty of down-scaling the full-scale model and being able to provide qualitative data from small-scale models. However, it is believed that the lab model accurately represents the full-scale model and therefore yields valid results.

Figure 3: Picture of the WavePiston model during the tests in the lab.

The model and its PTO system were designed and provided by the client. The PTO system consists of a sliding rail with weights for the loading, a LVDT (Linear variable differential transformer) to measure the displacement and a force transducer to measure the force. Since there were only two complete PTO systems, one was placed to measure the front plate and the other was placed to measure the rear plate. Each plate measured 0.5m x 0.1m (width and height) and was able to stay close to the water surface through some applied buoyancy on the plates, which were able to slide up and down on their support. During all tests, the distance between the two instrumented plates was 2.4m. When 4 plates were mounted the inter-plate distance was 0.8 m unless anything else was stated.

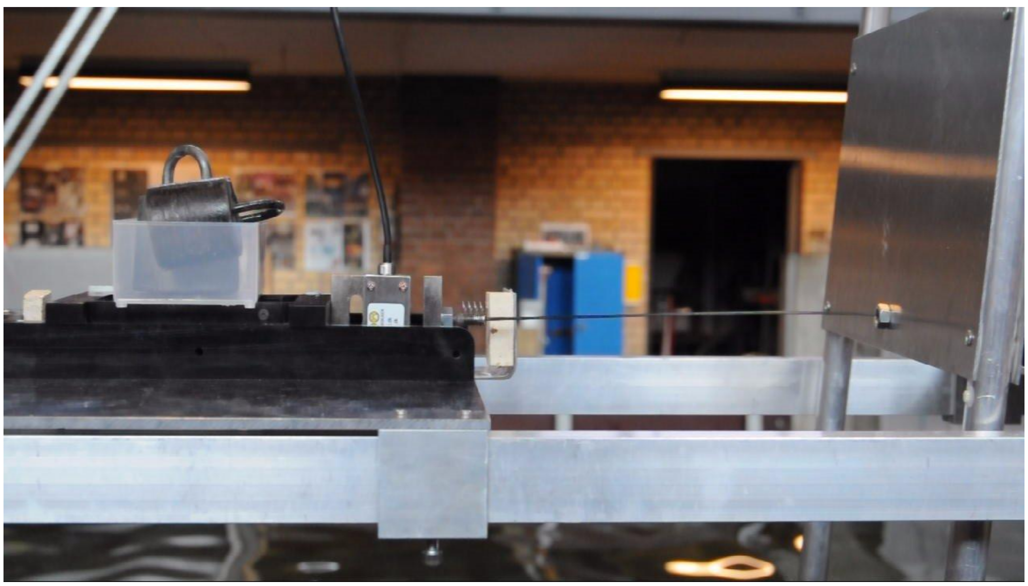
The instantaneous mechanical power (P) of a device can be defined by

$$P(t) = |\boldsymbol{F}(t)| \cdot |\boldsymbol{v}(t)| \tag{1}$$

From this instantaneous mechanical power, the average gives the amount of power that is converted from the wave into useful mechanical power over time, which could be compressed seawater as envisaged in the full-scale model. This does not take into account the efficiency of the PTO system nor the losses in the system converting this to electricity.

The force (F) that is transmitted through the interaction of the waves on the plates to the structure is measured with a force transducer. This sensor consists of strain gauges that are set in a Wheatstone Bridge. The change in force will strain or relax the strain gauges, changing their electrical resistance; hence the output will be a varying voltage. The voltage was calibrated with a known set of forces, which resulted in a linear relationship, and the equation of this relationship was stored by the data acquisition software.

The velocity (v) is calculated from measuring the position of the sliding load box, which is connected to the force transducer and mounted on a rail, by a LVDT. The linear velocity is then obtained by dividing the instantaneous change in position by the sampling time.



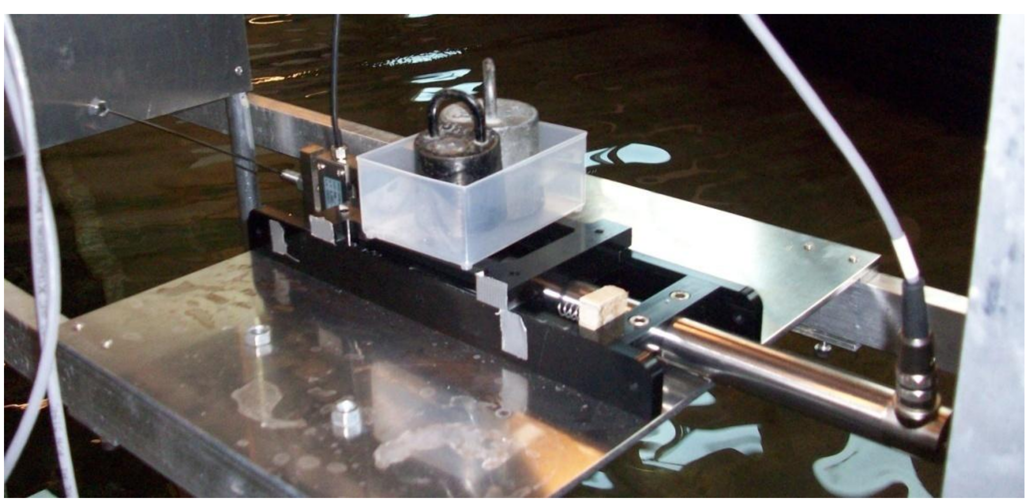


Figure 4 and 5: The PTO system, including the force transducer, the load setting by weights and the LVDT.

The performance of the device was tested with various loads. These loads (weights from 1 – 4 kg) were placed in a box located on the rail which connects the force transducer to the linear displacement sensor. A higher load would increase the pressure of the box on the rail (due to friction) and therefore increase the resistance to the movement.

The performance of the device is given for the average of the two instrumented plates and for the standardized Danish North Sea, Kofoed & Frigaard (2009), at a scaling ratio of 1:30. The wave parameters of these wave states, such as the Hs, Tp and Wp, are based on a 30m deep location and only the related efficiency was taken from the lab tests. The summarizing table states the efficiency, the average mechanical energy available to the PTO system of the device, the yearly mechanical energy production of the device and the load factor is calculated for 1 single plate. These were defined are calculated as:

- The 'Efficiency' is the ratio between the converted energy from the waves into useful mechanical energy and the available wave power for the same width. In the lab tests, this corresponds to dividing the average power, calculated by the transmitted force and velocity of the PTO system, by the corresponding wave power, set relative to the same width. This can be given individually for every wave state or as an average over the whole year:

$$\text{Efficiency}_{WS}\ [\%] = \text{Pmechanical (WS)/ Pwave (WS)} \quad (2)$$

$$\text{Efficiency}_{average}\ [\%] = \sum_{WS=1}^{5} \text{Efficiency (WS) x Probability of occurrence (WS)} \quad (3)$$

- The 'Energy production' represents the average transmitted power of a wave state set on a year bases. This corresponds to multiplying the average available power of the wave in that wave state by the efficiency and by to the probability of occurrence of that wave state. The sum of the energy production of every wave state gives the yearly average available mechanical power to the PTO system. From this yearly average energy production, the yearly total energy production can be calculated.

$$\text{Energy production}_{WS}\ [kW] = \text{Pwave (WS) x Efficiency (WS) x Probability of occurrence (WS)} \quad (4)$$

$$\text{Energy production}_{average}\ [kW] = \sum_{WS=1}^{5} \text{Energy production (WS)} \quad (5)$$

$$\text{Yearly Energy production [MWh/year]} = \text{Energy production}_{average} \text{ x } 365.25 \text{ x } 24 / 1000 \quad (6)$$

- The 'generating Power' is the average generated power in a particular wave state and corresponds to the efficiency of the device multiplied by the average available power in the waves in that particular wave state. The maximum of these generating power values is taken as the rated/installed capacity of the PTO system

$$\text{Pgen}_{WS}\ [kW] = \text{Pwave (WS) x Efficiency (WS)} \quad (7)$$

- The 'load factor' represents the average usage of the installed capacity, here set to the average generated power in the highest of the tested wave states.

$$\text{Load factor [-]} = \text{Energy production}_{average} \text{ / Pgen (max)} \quad (8)$$

3. Test Program

3.1 Overview

A comprehensive overview of the tests performed on the WavePiston model is given in the table below. First, a broad range of tests has been made with regular waves in order to create a first appreciation of its behaviour and verify some general assumptions. These tests were utilized to choose the appropriate scaling ratio and identified the range of application of the load setting, of movement of the components, and of the instrumentation.

Test Program	2 plates mounted	4 plates mounted
REGULAR WAVES		
Load identification	X	
Oblique waves		X
Wave Period dependency		X
Wave Height dependency		X
IRREGULAR WAVES		
Load setting optimisation	X	
Performance analysis	X	
Oblique waves		X
Various inter-plate distances		X

Table 1: Test program.

The initial tests with regular waves were then complemented with tests using irregular waves in order to fine-tune the load setting and to create a more realistic representation of the open sea. The irregular wave tests were normally carried out over a period of 30 minutes(corresponding to >1000 waves), following the JONSWAP spectrum at an enhancement coefficient of 3.3, while the regular waves were only run for 3 minutes.

The data files, from which the results are summarized in the appendix, are named as follow: e.g. IR_067_128_4x80_15_a20_01 is the Irregular wave (following the JONSWAP spectrum) with an Hs of 0.067m; Tp of 1.28s; 4 plates equally spaced at 0.8m; load of 1.5 kg; 20 degrees angle of attack of the incoming waves and corresponding test number 01. When one of these specifications is missing, their basic setup value should be taken.

3.2 Load setting

The optimal load corresponds to the one maximising the power production and therefore creates the optimal trade-off between transmitted force and linear velocity of the plates. For the full-scale model the load setting is intended to be adaptable in function of the incoming waves; however, here a constant load was used over all the different wave states.

The identification of this optimal load was first done with regular waves as they give a decent approximation and is much faster. They were followed by irregular wave tests in order to fine-tune and confirm the right load. It has been decided to go for the 1.5kg load; however, an even more optimal load setting could be found by doing more tests.

3.3 Efficiency, Energy Production and Wave State tests

It was decided to evaluate the power production performance of the device for the Danish part of the North Sea where the WavePiston device could be implemented for full-scale energy production. The standardized wave states describing the energy in the Danish seas from Kofoed and Frigaard (2009) are used here. The wave conditions are given in table 2, where Hs is the significant wave height, Tz is the average zero-crossing wave period, Tp is the peak period of the wave spectrum and the wave power flux is given in average available power per meter per wave state together with the corresponding probability of occurrence.

The Danish North Sea						1:30 (Irregular)				1:30 (regular)		
Wave State	Hs [m]	Tz [s]	Tp [s]	Energyflux [kW/m]	Prob [%]	Wave State	Hs [m]	Tz [s]	Tp [s]	Wave State	H [m]	T [s]
1	1.0	4.0	5.6	2.4	46.8	1	0.033	0.73	1.02	1	0.024	1.02
2	2.0	5.0	7.0	12.0	22.6	2	0.067	0.91	1.28	2	0.047	1.28
3	3.0	6.0	8.4	32.3	10.8	3	0.10	1.10	1.53	3	0.071	1.53
4	4.0	7.0	9.8	67.0	5.1	4	0.133	1.28	1.79	4	0.094	1.79
5	5.0	8.0	11.2	119.7	2.4	5	0.167	1.46	2.04	5	0.118	2.04

Table 2: Overview of the irregular and regular wave parameters of the standardized wave states describing energy in the Danish seas from Kofoed and Frigaard, 2009.

The values stated in the table are targets when generating the waves. In reality, the realized and/or observed waves might be slightly different, due to all the influential parameters, such as the reflection in the basin, margin of uncertainties of the generating equipment and many other small details. However, all the results of the test have been handled on the same way and all the data has been processed thoughtfully in order to present the most accurate data. In the analyses, the actual recorded wave parameters have been used rather than the targets.

3.4 Wave period and wave height dependency

The wave height dependency tests consist of varying the wave height, from 0.03 to 0.11m with increments of 0.02, while keeping the wave period constant at 1.2s. During the wave period dependency test, the wave height was kept constant at 0.06m, while the wave period ranged from 0.6s until 1.8s with increments of 0.2s. The testing range of the variables was chosen in function of the limits of the equipments. The resistance of the model fixed the highest wave parameters, while the limits of the instrumentations and the basin, to give good quality data, were used to choose the lowest wave parameters. A constant wave height of 0.06m was chosen for the test as it is intermediate to the wave height of wave state 1 and 2, where the model performs well and the instrumentation can provide qualitative measurements. The constant wave period of 1.2s was chosen for the same reasons as the wave height but also because the results of the other test seemed to have an strange behaviour around this wave period.

These tests were only run with regular waves in order to analyse the dependency of the model to one particular wave length and not to a whole wave spectrum.

3.5 Oblique waves

The WavePiston WEC model was tested in wave state 2 and 3 (0.067m – 1.28s and 0.1m – 1.53s) for three different angles of attack of the incoming wave of 10, 20 and 30 degrees. Results are given for the tests with irregular waves with 4 plates mounted on the frame. This investigation could give some insight over the mooring design (e.g. whether it should have a fixed direction or be allowed to rotate to face the predominant direction of the incoming waves).

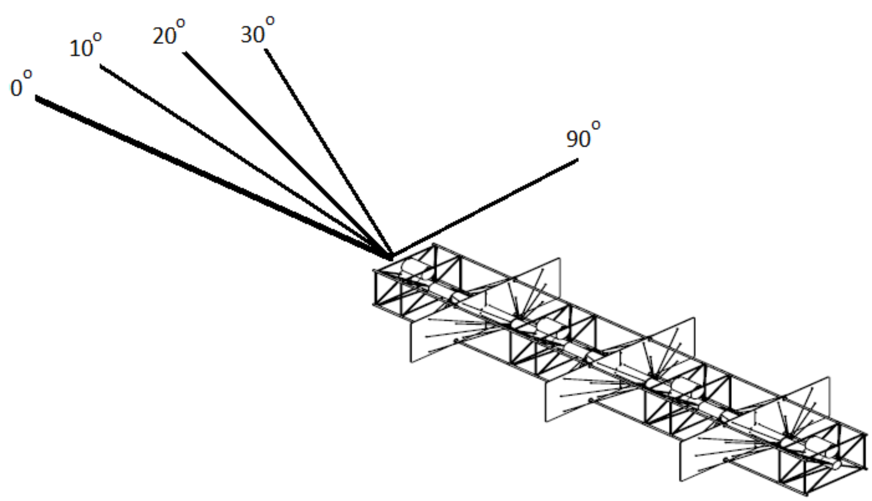


Figure 6: Illustration of different angles used for the directional wave tests.

3.6 Inter-plates distances

The test setup were performed with 4 plates mounted and the performance of the device has been investigated for 3 different inter-plate distances, 0.45, 0.55 and 0.8m, and 2 wave states, 2 and 3. Results are given for the first and rear plate, as only these were equipped with a PTO system and relative to the reference case, which was the 2 plate setup with 2.4m as inter-plate distance. The results of these tests could determine the distance between the plates required to minimise the loss in power from plate to plate or to find a distance that has some other beneficial interaction, such as resonance due to reflection.

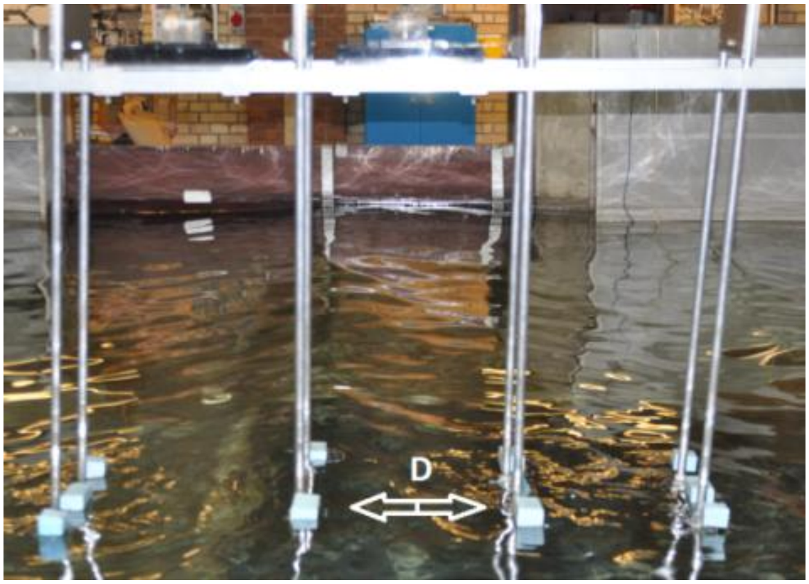


Figure 7: Illustration of the distance in between the plates.

4. Results

4.1 Load Setting

Initially, various tests were made with regular waves in order to identify the range of the optimal loading and scaling ratio. It has been decided to use the 1 to 30 scale as it would represent the most appropriate trade-off between what is assumed to be physically possible in full-scale and what might give the best hydraulic performance of the model. The tests with regular waves also showed that the optimal load would be close to 2.5kg, which can be observed in Fig.8.

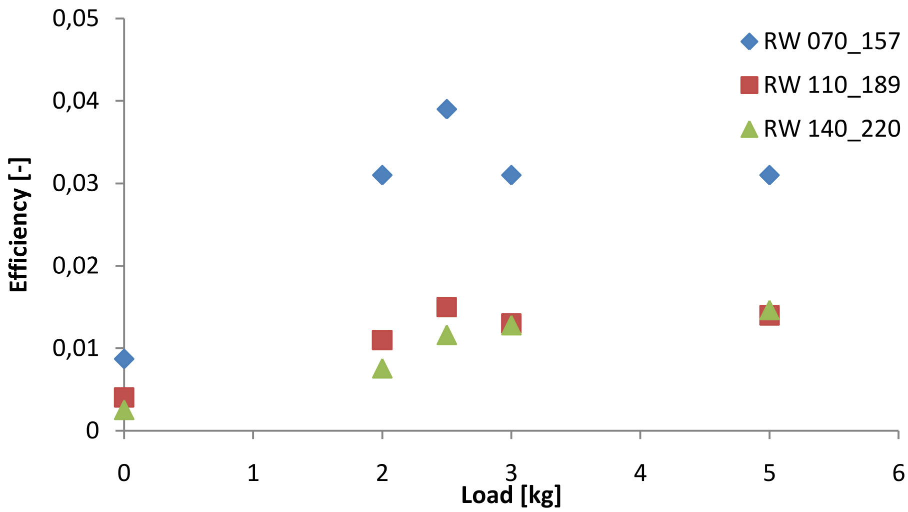


Figure 8: Load identification for 3 different regular waves: 0.07m- 1.57s, 0.11m – 1.89s, 0.14 – 2.2s.

Due to some limitation in time, only two tests were then repeated in irregular waves to identify the best load. It was chosen to repeat the 1.5 and 2.5kg loads, due to the excessive static friction for higher loads and excessive motion of the load wagon on the sliding rail for lower loads. The difference in results can be seen in the next figure.

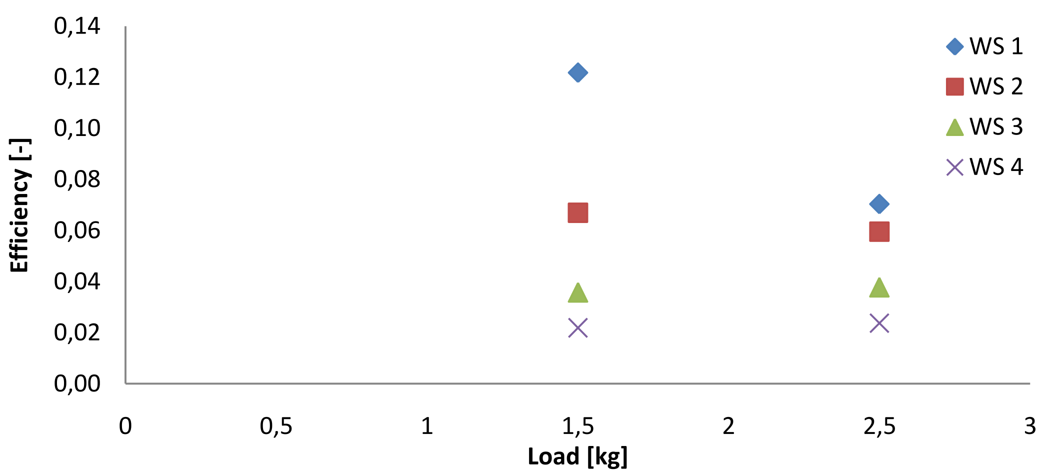


Figure 9: Load optimalisation in irregular waves for 2 different loads and 4 different wave states.

In irregular waves, the load of 1.5kg gave the “best” results and was found the give the most reasonable trade-off, between the static friction and the motion of the load wagon, for the model. In general, the difference is small except in the lowest wave state. In wave state 2 the gain in efficiency, for the 1.5kg load, is already significantly reduced and for wave state 3 and 4 it even appears to be slightly lower. These results could suggest using a higher load for greater wave state and that some further tests with an intermediate load might be useful.

The next figure contains the standard deviation of the force in these different wave states and for the two different loads, as it is believed that this might be the best way to represent the load. Surprisingly, their value does not exactly behave similarly as the load of 1.5 kg has a standard deviation value that fluctuates between 6 and 7N, while one of the 2.5kg load increases with the wave states from 7.1 till 10.5N. This might be due to the different behaviour of the box on the sliding rail, such as the static friction which varied depending on the load and the wave state.

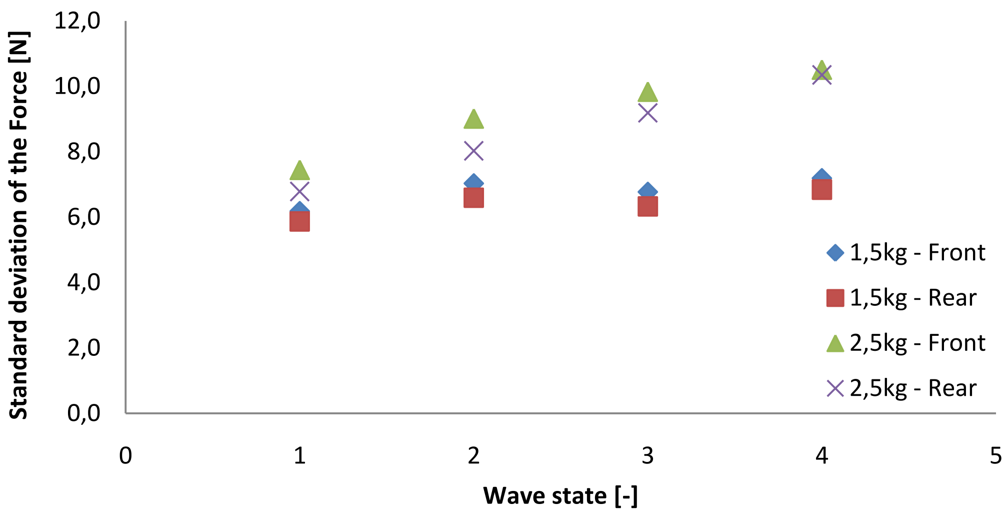


Figure 10: Corresponding standard deviation of the force relative to the load and wave state in irregular waves

Even if the load setting mechanism was very easy to use and worked very well throughout all the test, it does not seem to be very constant as its values fluctuate depending on the wave parameters. These had an indirect influence on the static pressure.

4.2 Efficiency, Energy Production and Wave State tests

The next graph summarizes the estimated efficiency of 1 individual plate of the WavePiston model for the wave states characterising the Danish North Sea. Decent and consistent results have been found for the first four wave state, but unfortunately it does not contain a result for wave state 5, as the transmitted forces and resulting movements of the plates were excessive for the model. However, this result seems not to be of great interest as it would probably tend to be very low, estimated to approximately 0.012.

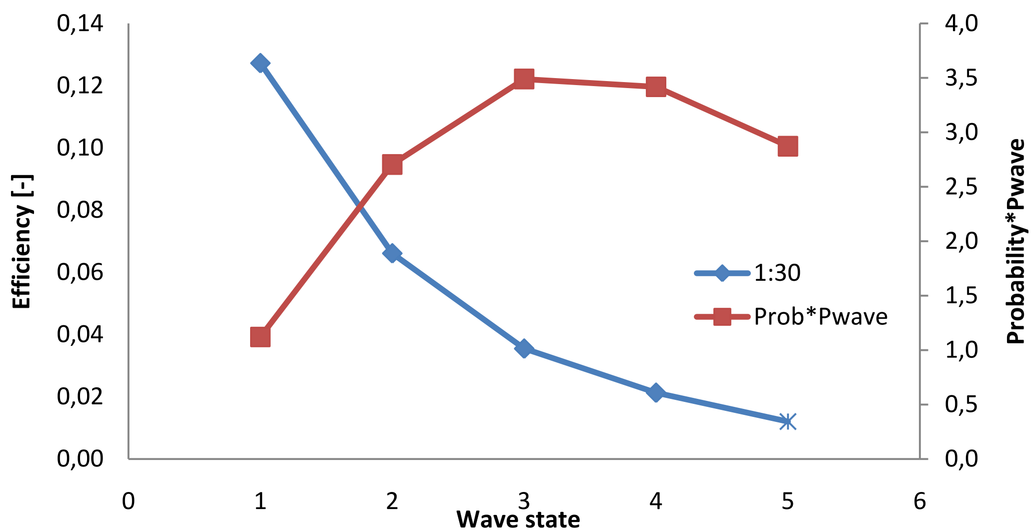


Figure 11: Representation of the average efficiency of one plate of the prototype tested at the different wave states in irregular waves. The blue line is dependent on the efficiency (left side) where the red line belongs to the Probability×Pwave scale on the right. The performance value in wave state 5 is estimated.

We can observe that the efficiency, which is the ratio of the transferred energy by one plate to the available wave energy, is greatest in the lowest wave state. A value of 0.127 is found in wave state 1, which decreases to 0.066 in wave state 2 and follows the same trend in the 3 next wave states. From a performance point of view, it would be conceivable to increase the scaling ratio, which would translate the whole efficiency curve to higher wave states (to the right) and therefore increase the average performance and total energy production per device. However, conceptually and structurally speaking, this will most probably significantly increase the forces on the structure and the components, increasing the capital costs and making it no longer physically possible. From a survivability and economical point of view, it might go either way, as fewer but larger structures might be advantageous.

The load of the PTO system of the 1:30 scale model consisted only of the friction due to a weight. The return force of the plate to its neutral position was hence very small as it was only subject to the waves and its own weight. In full-scale, there will probably be a spring system (or similar) in order to ensure that the neutral position is maintained and to avoid excessive end-stop forces. This might furthermore bring the system in resonance in some cases.

The following table summarizes the performance and shows the estimated energy output of the full-scale WavePiston WEC per m width of plate, set perpendicular to the incoming wave. The yearly average generating power level is approximately 0.55 kW/m, as the average efficiency is around 0.08 and the yearly average available wave power around 13.61kW. This correspond to a yearly energy production per meter of 4.84 MWh/year/m and a load factor of the PTO system of 0.38.

Wave State	Pwave [kW/plate]	Prob [%]	Prob*Pwave [kW/m]	Efficiency [-]	Energy prod. [kW/plate]	Pgen [kW/plate]
1	36	46,8	16,81	0,13	2,14	4,57
2	180	22,6	40,58	0,07	2,68	11,87
3	485	10,8	52,35	0,04	1,86	17,19
4	1005	5,1	51,28	0,02	1,09	21,38
5	1795	2,4	43,09	0,01	0,52	21,55
Overall efficiency [-]				0,08		
Average Power [kW/plate]			204,10		8,29	
Yearly production/plate [MWh/y/plate]					72,63	
Max. Pgen [kW/plate]						21,55
Load factor [-]						0,38

Table 3: Summary of the performance and the estimated energy that can be converted from the waves into useful mechanical energy by one plate (15m wide) of the Wavepiston WEC model.

4.3 Wave period and wave height dependency

In the next graph presents the efficiency of the WavePiston model for a constant wave height of 0.06m and varied wave periods. The values are the combined result of the two plates, front and rear of the four mounted plates spaced equally at 0.8m.

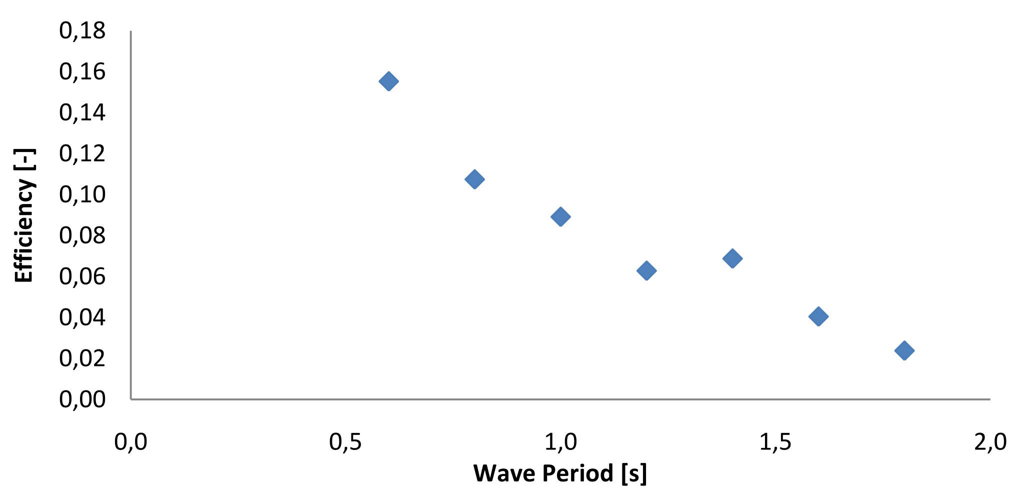


Figure 12: This graph presents the effect of the wave period on the average performance of the model, having 4 plates mounted that are equally spaced at 0.8m, at a constant wave height of 0.06m.

The curve, between the performance and the wave period, appears to be rather consistent, with a smooth decrease in performance with higher wave periods. However, a small but obvious peak can be noticed around 1.4s. This could be related to the load, as it would be possible that the performance is maximal around this wavelength for this particular load. It would be possible to imagine that the curve in the previous figure is the sum of 2 curves: 1 diminishing from left to right due to the loss in efficiency and another having a peak around 1.4s due to the relationship between the load and wave period. In this case, another load might create another peak at another wave period. However, other reasons such as change in the fluid pattern around this wave period resulting in less turbulence might be possible too.

The next graph states the standard deviation of the force found for the front and rear plate. It proves that the load was relatively constant over all the tests and had therefore no influence on the curve of Fig.12.

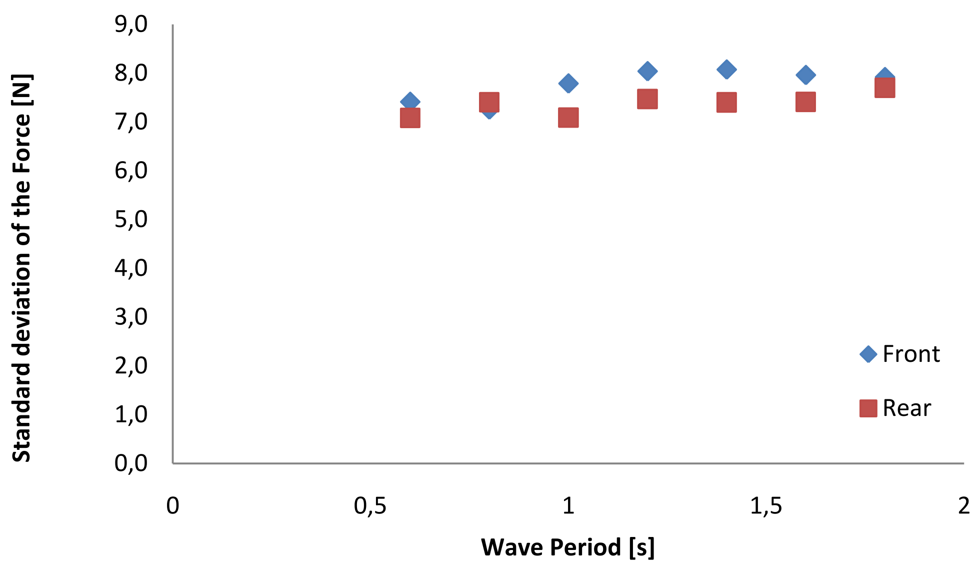


Figure 13: This graph presents the standard deviation of the load on the front and rear plate of the 4 mounted plates during these tests, regular waves at 0.06m and various wave periods at a load of 1.5kg.

In order to have a closer look at these results, the next graph contains the individual performance results of the front and rear plate relative to a different reference (the wavelength divided by the inter-plate distance). Both curves contain the small peak at 1.4s and the back plate tends to perform less well. This is probably due to the sheltering effect from the other plates as the efficiency is greater in smaller waves, which means that more energy relatively gets extracted out of the smaller waves. However, the relative difference in between the two plates is almost the same, for the longest waves as for the shortest waves. Some more investigation should be done around this wavelength in order to see why this peak appears and what it is linked with.

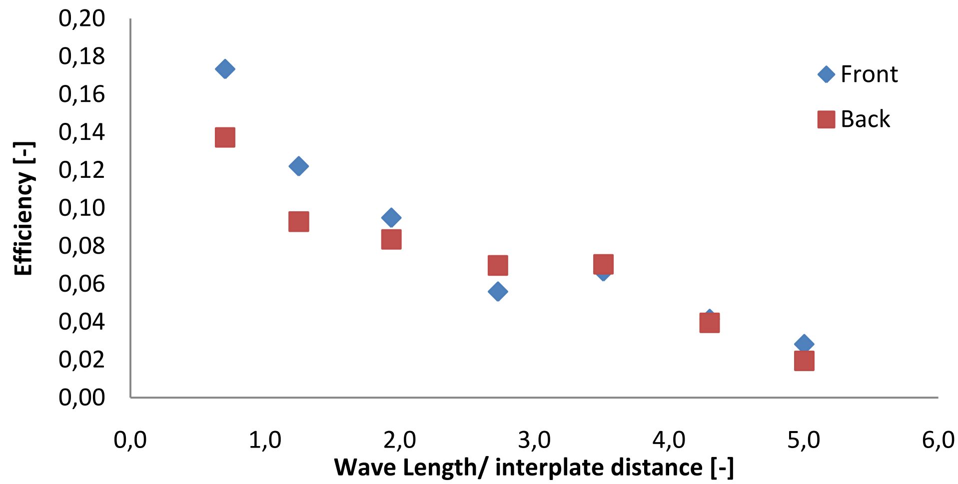


Figure 14: This graph shows an initial study on how the device behaves at a range of wave periods given a wave height of 0.06m for different loading settings with regular waves, having 4 plates mounted at 0.8m inter-distance.

The performance of the individual plates of the device is dependent on the wavelength, with increasing performances with decreasing wave lengths. This dependency is true in this particular case of a fixed structure with plates of 0.5 x 0.1m spaced 0.8m. However, this dependency might be different if one of these parameters is modified.

Fig. 15 contains the results for a constant wave period of 1.2s and various wave heights. It can be noticed that the influence of the wave height on the performance is less than of the wave period, but that it still is a relevant influential parameter. The performance tends to decrease approximately linearly from 0.06 to 0.03 for waves ranging from 0.03m to 0.11m

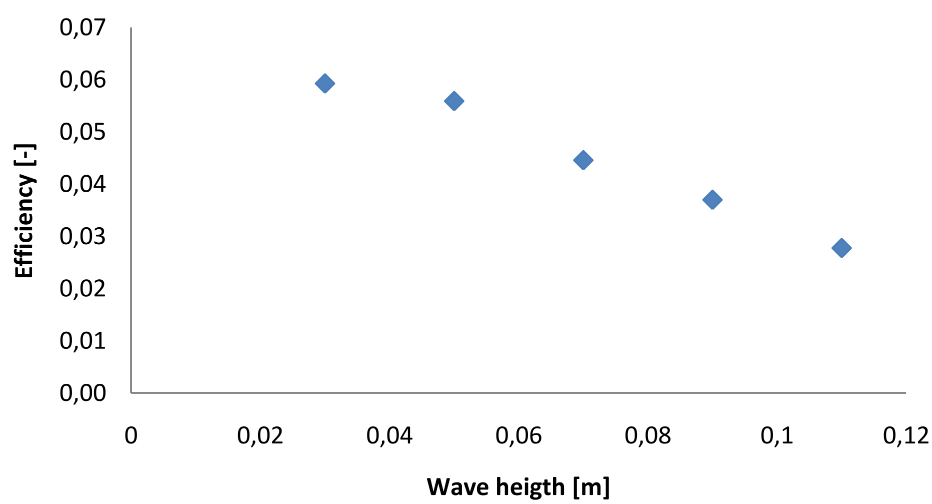


Figure 15: This graph shows how the WavePiston model performs, combining the results from the front and rear of the 4 equally spaced plates at 0.8m, at different wave heights and a given wave period of 1.2s in regular waves.

The decrease in performance might be due to losses related to turbulence. As the water particles have a greater velocity for higher waves, these might result in more disturbance/turbulence in the flow passing next to the plates, hence diminishing the drag on the plates.

4.4 Oblique waves

The influence of the angle of attack of the incoming wave on the performance of the WavePiston model has been tested for three angles, in two different wave states, 2 and 3. The results are given relative to the reference setup, where the angle of attack of the incoming wave was 0 degrees. During these tests, 4 plates were mounted on the model at 0.8m, equally spaced.

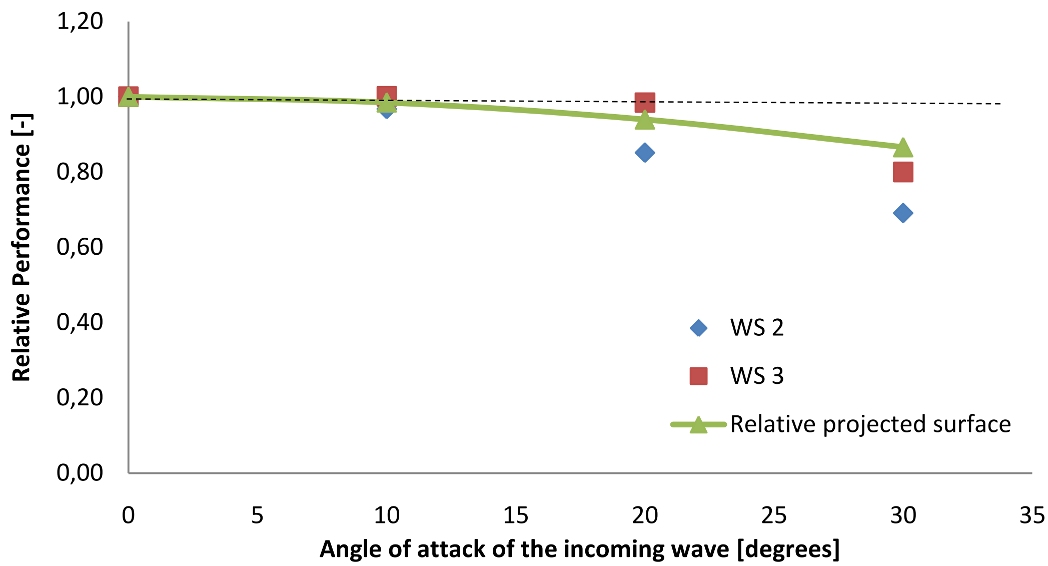


Figure 16: This graph shows the effect of directional waves on the performance of the WavePiston model for irregular waves of wave state 2 and 3, 0.07m - 1.28s and 0.10m – 1.53s.

The results illustrate that the loss in performance increase progressively to 25% for an angle of 30 degrees. The loss in performance is more pronounced for the smaller wave state than for the greater one, but in both cases the results were very similar for the front as for the rear plate, demonstrating that the plates do not influence each other in this case. The relative projected surface facing the incoming waves closely follows this decreasing trend of the performance, especially in the smallest angles. For greater angles of the incident wave, the wave might more and more slide or being redirected by the plate, resulting in another source of loss besides the reduced projected area.

These results show that the structure does not need to exactly face the waves and could perform well with oblique waves of a fairly large angle of attack, which would give further flexibility to the mooring setup. In the case where the window of the incoming waves at a location is quite small (±45degrees) almost no freedom of rotation of the device would be needed. Furthermore, the influence of short-crested waves (3D waves as been found in open seas), often composed of waves coming from different directions, might also be limited.

4.5 Inter-plate distance

The next graph presents the influence of the inter-plate distance for three different distances, spacing the 4 plates equally and this for 2 different wave states: 2 and 3. The results are given individually for the front and rear plate and relative to the reference setup, where the two plates were spaced at 2.4m.

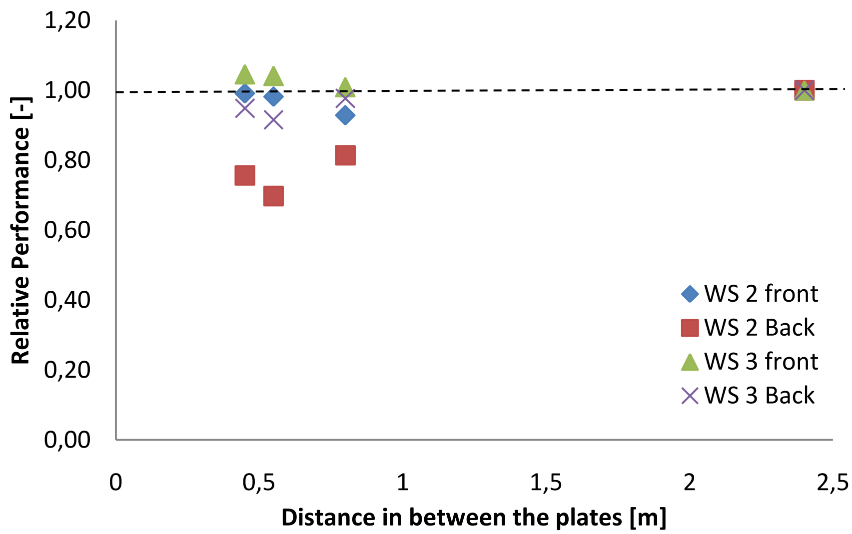


Figure 17: This graph shows the effect of the inter-plate distance on the performance of the WavePiston model for irregular waves of wave state 2 and 3, 0.07m - 1.28s and 0.10m – 1.53s.

Greater losses in performance can be noticed for smaller inter-plate distances, while keeping the wave characteristics constant, and that the effect is much more pronounced in wave state 2 as in wave state 3. For wave state 2, a spacing of 0.8m has already a significant impact on the performance, while for the same distance the loss is negligible in wave state 3. The relative efficiency drop appears for both wave states to be greater for an inter-plates distance of 0.55m than for 0.45m. This might be due to the diffraction of the waves around the plate, focusing the waves better on the next plate. The relative performance of the front plate, in the case of wave state 3, increases with shorter inter-plate distances. This might also be due to the diffraction and reflection on the rear plate. If the diffraction is really the cause of these trends, then it could have a similar effect, when several of these devices will be placed in an array. Some further tests might reveal many of these hypotheses.

If we present the same results differently, by using the wavelength relative to the inter–plate distance as a reference, we can observe that for the same ratio different results are found. For example, at a ratio of 4, the front and rear plate perform equally well in wave state 3, which is not the case for the wave state 2. This is probably due to other predominant influential parameters such as the effect of the width and/or depth of the plates on the required inter-plate distance for the waves to totally recover in power.

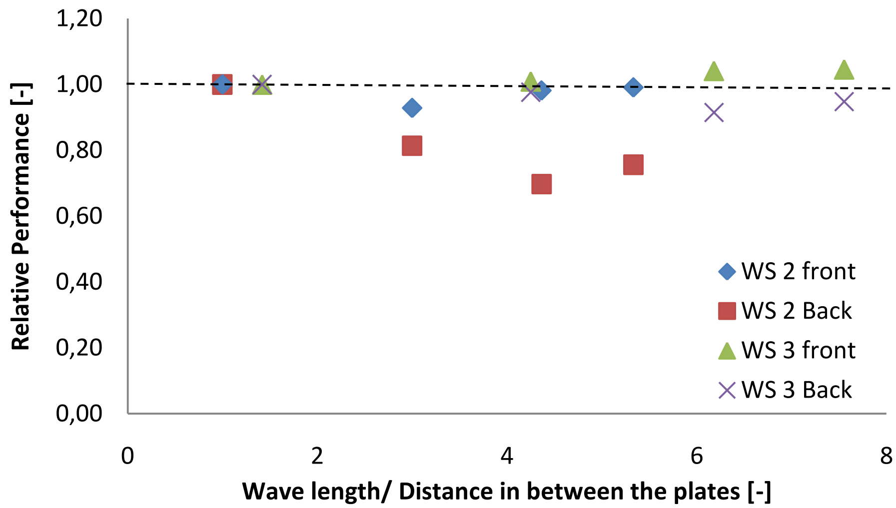


Figure 18: This graph shows the effect of the wavelength to inter-plate distance ratio on the performance of the WavePiston model for irregular waves of wave state 2 and 3, 0.07m - 1.28s and 0.10m – 1.53s.

The right distance in between the plates seems to be dependent on various parameters, such as the wave parameters, the angle of attack of the incoming wave and probably the plate design. So while this investigation provided a better understanding of the device, it is recommended that additional tests are made.

5. Conclusions

5.1 General

The performed study was the first investigation on the WavePiston model and can be considered as a proof of concept, as the WavePiston WEC is able to convert energy in the waves into useful mechanical energy, which then, through further mechanical and electrical systems, could be converted into electricity.

The average power production capabilities of the WavePiston WEC have been estimated for a reference offshore location of the Danish North Sea and investigations on the effect of various variables on the performance have been carried out. It is believed that various possibilities exist to further improve the performance and that the concept has a lot of flexibility in its design, e.g. the amount of plates or other parameters could be adapted in function of the location of interest.

5.2 Observations

The tests have been made on a 1 to 30 scaled model of the WavePiston WEC. The structure and PTO system have been adapted to suit the model and give accurate data. The corresponding full-scale model would have plates of 15x3m width and height instead of 0.5x0.1m, as used for the model. From examination of the results presented in Section 4 the following conclusions have been drawn:

- A load of 1.5 kg, which corresponds to almost 7N as standard deviation in the transmitted force through the plates, has been used as load. Some more refining work on the load could enhance the performance even further.
- The yearly average energy that one plate of the WavePiston WEC would convert from the waves into mechanical energy is estimated to be around 72,63MWh/plate/year, which corresponds to an average efficiency of 8%. The efficiency has been found to decrease exponentially from 12.2% in wave state 1 to 2.2% in wave state 4 for a 1:30 scale. No tests were run in wave state 5 as this could have ruined the equipment. A higher scale of e.g. 1:40 or 1:50 is believed to increase its performance considerably but at the expense of higher loads.
- From the test mapping the dependency of the performance of the device to the wave height and wave period, it was concluded that they both have a moderate to significant influence on the performance. In both cases the performance increased with a decreasing wave height and wave period. At around 1.4s, a peak in performance was observed relative to the general trend of the curve, further testing at periods close to this would be useful.
- Testing the device in oblique waves showed that the efficiency dropped only slightly with increased angle of attack to the waves over the range tested. This drop in performance was found to be around 2%, 8% and 25% for angles of attack of 10, 20 and 30 degrees respectively in wave state 2 and 3.
- In wave state 3 and for an inter-plate distance of 0.8m in the lab, the wave will reform (almost) completely before getting to the next plate. In wave state 2, a longer distance would be needed. So the smaller the wavelength, the more distance is required for the wave to recover.

This might be due to the fact that the performance of the plates is higher in smaller wave states and therefore more power recovery has to be done. Moreover, the diffraction pattern of the waves around the plate might have an influence on the performance, reducing the loss for a specific short distance and increasing the performance for others.

5.3 Suggestions

In general, the results obtained during this experimental study are giving a very good indication of the behaviour of the WavePiston WEC, however, so far only a small part of the device has been investigated. Here for, the following are proposed areas of investigation for the further development of the device:

- The choice of the most feasible scaling ratio. A greater scaling ratio would most probably considerably increase the average performance and power production of the device. However, from the mechanical and structural point of view, a greater scaling ratio would enhance stresses and loads. The mechanical and structural limitations should be investigated thoroughly in order to identify the right size.
- The PTO system was composed during these tests of a fixed load (weights), while the full-scale PTO system might consist of an adaptable load and some other components such as springs, in order to keep the plates in place and/or reduce end-stop forces. This change in setup might result in a different load and maybe even a different performance curve.
- Further investigation should be made on the right inter-plate distance, the amount of plates (as envisaged in full scale) and on the main relevant parameters, such as the design of the plates.
- The design (size, density, rigidity ...) of the plates might be subject for improvement as some studies have shown that the design of plates of oscillating wave surge converters influences the average performance.
- As the full-scale WavePiston WEC design is intended to have a floating structure with a flexible mooring instead of a fixed structure, as was used for the tests in the lab, the tests varying the distances in between the plates should be repeated with a flexible mooring instead of the fixed while measuring the mooring forces and the performance. The observations might be different, as the flexible moored structure may move differently for different wavelengths and/or wave states, and therefore perform less well.
- The result of the tests concerning the influence of the wavelength on the performance of the plates while keeping the wave height constant showed a particular behaviour around 1.4s. On a first instance this might not be the most important, but it might be interesting to investigate this phenomenon further.
- The interaction of WavePiston WEC should also be subject of one of the future investigations as their might be a specific distance for which the interaction is beneficial or some distances to avoid.

A thorough literature study might already give good indications on some of these topics, as other device, of the same type or not, have already analysed similar subjects.

6. References

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7. Appendix – Test results

Filename	Wave power [W/m]	H - Hs [m]	T - Tp [s]	Power [W/m] Front	Rear	Overall	Efficiency Front	Rear	Overall
front									
RW 070_157_240_00_03	7,95	0,067	1,60	0,066	0,07	0,068	0,008	0,009	0,009
RW 110_188_240_00_02	24,83	0,108	1,83	0,088	0,09	0,089	0,004	0,004	0,004
RW 140_220_240_00_01	52,73	0,158	2,13	0,134	0,13	0,132	0,003	0,002	0,003
RW 070_157_240_20_01	7,01	0,065	1,60	0,182	0,254	0,218	0,026	0,036	0,031
RW 110_188_240_20_01	25	0,112	1,83	0,244	0,306	0,275	0,010	0,012	0,011
RW 140_220_240_20_01	54,31	0,161	2,13	0,412	0,5	0,456	0,008	0,009	0,008
RW 070_157_240_50_01	6,33	0,063	1,60	0,18	0,218	0,199	0,028	0,034	0,031
RW 110_189_240_50_01	28,59	0,119	1,83	0,404	0,372	0,388	0,014	0,013	0,014
RW 140_220_240_50_01	53,51	0,164	2,13	0,782	0,792	0,787	0,015	0,015	0,015
RW_070_157_240_30_01	8,19	0,068	1,60	0,252	0,258	0,255	0,031	0,032	0,031
RW_110_188_240_30_01	28,16	0,116	1,83	0,382	0,35	0,366	0,014	0,012	0,013
RW_140_220_240_30_01	56,7	0,164	2,13	0,728	0,73	0,729	0,013	0,013	0,013
RW_070_157_240_25_01	8,1	0,069	1,60	0,32	0,312	0,316	0,040	0,039	0,039
RW_110_189_240_25_01	27,98	0,122	1,83	0,452	0,398	0,425	0,016	0,014	0,015
RW_140_291_240_25_01	56,9	0,164	2,13	0,666	0,7	0,683	0,012	0,012	0,012
RW_035_125_240_25_01	1,82	0,038	1,28	0,112	0,128	0,12	0,062	0,070	0,066
IR_067_128_240_25_01	2,57	0,063	1,28	0,15	0,156	0,153	0,058	0,061	0,060
IR_033_102_240_25_01	0,27	0,023	1,05	0,016	0,022	0,019	0,059	0,081	0,070
IR_100_153_240_25_01	7,3	0,095	1,51	0,274	0,278	0,276	0,038	0,038	0,038
IR_133_179_240_25_01	17,14	0,133	1,77	0,408	0,406	0,407	0,024	0,024	0,024
IR_167_204_240_25_01	-	-	-	-	-	-	-	-	-
IR_100_153_240_15_01	6,67	0,090	1,55	0,238	0,24	0,239	0,036	0,036	0,036
IR_067_128_240_15_01	2,33	0,060	1,28	0,148	0,162	0,155	0,064	0,070	0,067
IR_033_102_240_15_01	0,23	0,021	1,05	0,024	0,032	0,028	0,104	0,139	0,122
IR_133_179_240_15_01	15,47	0,126	1,77	0,338	0,34	0,339	0,022	0,022	0,022
IR_067_128_4x80_15_01	2,51	0,062	1,28	0,148	0,142	0,145	0,059	0,057	0,058
IR_100_153_4x80_15_01	6,83	0,091	1,60	0,246	0,24	0,243	0,036	0,035	0,036
RW_024_102_4x80_15_a10_01	0,38	0,019	0,98	0,066	0,032	0,049	0,174	0,084	0,129
RW_047_128_4x80_15_a10_01	2,89	0,046	1,28	0,116	0,162	0,139	0,040	0,056	0,048

RW_071_153_4x80_15_a10_01	7,59	0,066	1,60	0,312	0,254	0,283	0,041	0,033	0,037
IR_067_128_4x80_15_a10_01	2,47	0,060	1,25	0,142	0,134	0,138	0,057	0,054	0,056
IR_100_153_4x80_15_a10_01	6,74	0,091	1,51	0,242	0,238	0,24	0,036	0,035	0,036
RW_071_153_4x80_15_a30_01	7,61	0,067	1,60	0,248	0,25	0,249	0,033	0,033	0,033
RW_047_128_4x80_15_a30_01	2,89			0,13	0,118	0,124	0,045	0,041	0,043
IR_067_128_4x80_15_a30_01	2,23	0,058	1,25	0,09	0,088	0,089	0,040	0,039	0,040
IR_100_153_4x80_15_a30_01	6,99			0,198	0,2	0,199	0,028	0,029	0,028
IR_067_128_4x80_15_a20_01	2,40			0,122	0,114	0,118	0,051	0,048	0,049
IR_100_153_4x80_15_a20_01	6,71	0,091	1,51	0,24	0,23	0,235	0,036	0,034	0,035
RW_060_180_4x80_15_1	6,95	0,059	1,83	0,198	0,136	0,167	0,028	0,020	0,024
RW_060_160_4x80_15_1	4,77	0,052	1,60	0,198	0,188	0,193	0,042	0,039	0,040
RW_060_140_4x80_15_1	3,19	0,047	1,42	0,214	0,226	0,22	0,067	0,071	0,069
RW_060_120_4x80_15_1	4,1	0,059	1,16	0,228	0,284	0,256	0,056	0,069	0,062
RW_060_100_4x80_15_1	2,96	0,055	0,98	0,282	0,248	0,265	0,095	0,084	0,090
RW_060_080_4x80_15_1	2,69	0,061	0,80	0,326	0,248	0,287	0,121	0,092	0,107
RW_060_060_4x80_15_1	1,42	0,058	0,60	0,26	0,206	0,233	0,183	0,145	0,164
RW_110_120_4x80_15_01	16,36	0,117	1,22	0,496	0,414	0,455	0,030	0,025	0,028
RW_090_120_4x80_15_01	10,54	0,093	1,22	0,394	0,374	0,384	0,037	0,035	0,036
RW_070_120_4x80_15_01	6,15	0,072	1,22	0,288	0,262	0,275	0,047	0,043	0,045
RW_050_120_4x80_15_01	2,96	0,049	1,22	0,18	0,154	0,167	0,061	0,052	0,056
RW_030_120_4x80_15_01	0,79	0,027	1,22	0,028	0,068	0,048	0,035	0,086	0,061
IR_100_53_4x55_15_01	6,62	0,090	1,51	0,246	0,218	0,232	0,037	0,033	0,035
IR_067_128_4x55_15_01	2,31	0,059	1,25	0,144	0,112	0,128	0,062	0,048	0,055
IR_100_53_4x45_15_01	6,86	0,091	1,51	0,256	0,234	0,245	0,037	0,034	0,036
IR_067_128_4x45_15_01	2,32	0,060	1,22	0,146	0,122	0,134	0,063	0,053	0,058
Wave powers in grey are based on the average of test with identical wave parameters									
H and T correspond to regular waves, while Hs and Tp corresponds to irregular waves									

The data files are named as follow: e.g. IR_067_128_4x80_15_a20_01 is the Irregular wave (following the Jonswap spectrum) with an Hs of 0.067m; Tp of 1.28s; 4 plates equally spaced at 0.8m; load of 1.5 kg; 20 degrees angle of attack of the incoming waves and corresponding test number 01.