The Crest Wing Wave Energy Device

2nd phase testing

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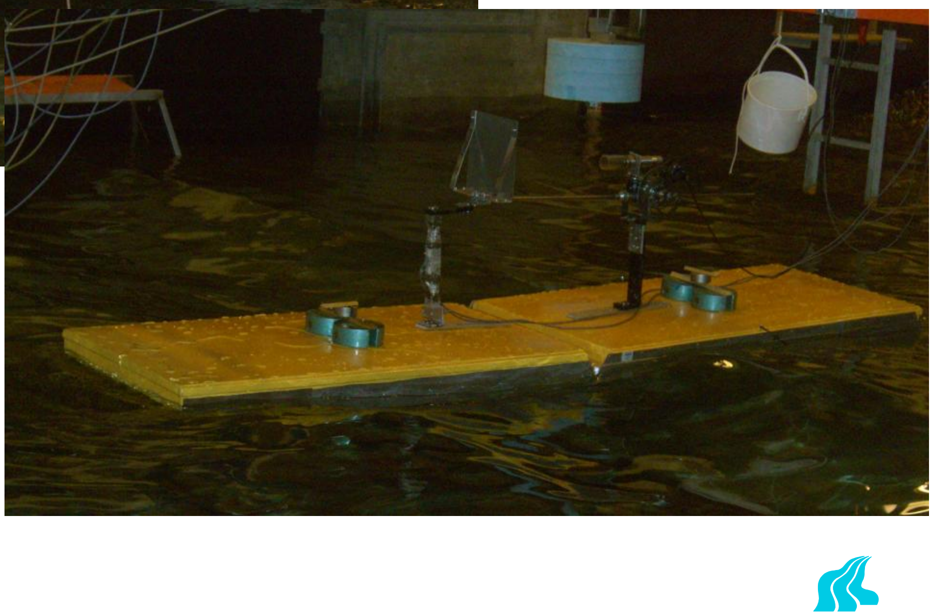

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by

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Preface

This report presents the results of a continuation of an experimental study of the wave energy converting abilities of the Crest Wing wave energy converter (WEC), in the following referred to as 'Phase 2'. The Crest Wing is a WEC that uses its movement in matching the shape of an oncoming wave to generate power.

Model tests have been performed using scale models (length scale 1:30), provided by WaveEnergyFyn, in regular and irregular wave states that can be found in *Assessment of Wave Energy Devices. Best Practice as used in Denmark* (Frigaard et al., 2008). The tests were carried out at Dept. of Civil Engineering, Aalborg University (AAU) in the 3D deep water wave tank. The displacement and force applied to a power take off system, provided by WaveEnergyFyn, were measured and used to calculate mechanical power available to the power take off.

The tests have been performed by Jens Peter Kofoed and Mike Antonishen, AAU, in co-operation with Henning Pilgaard, WaveEnergyFyn (referred to as 'the client'), who was present in the laboratory during the tests. The testing took place in December, 2008. The report has been prepared by Jens Peter Kofoed and Mike Antonishen (tlf.: +45 9635 8474, e-mail: jpk@civil.aau.dk).

Aalborg, March, 2009

Version	***Date***	***Author***	***Comment***
0.1	27.03.2009	JPK	First draft
1.0	30.03.2009	JPK/MA	Final version

Table of Contents

1. Introduction

The Crest Wing Wave Energy Converter is currently being developed by Henning Pilgaard, of WaveEnergyFyn, Denmark. For an introduction to the concept please refer to Kofoed & Antonishen (2008) who reported on the initial testing of the Crest Wing WEC.

The current study is a continuation of the study reported by Kofoed & Antonishen (2008), focusing on the relative reference setup, following up on the following issues:

- Skirt length optimization
- Inlet/outlet
- Influence of weight
- Horizontal skirt variations
- Scaling/sizing of the device

These items are treated in the following.

Values presented in the following figures and tables all refer to laboratory scale unless stated otherwise.

2. Test Setup

All testing was performed with models supplied by the client (at an assumed length scale of 1:30).

All data points were recorded at a sample frequency of 25 Hz.

The anchoring of the Crest Wing was recreated to match the test setup used by Kofoed & Antonishen (2008), exactly. The converter is anchored at both ends with springs and the characteristic of the anchoring system in calm water is presented in Figure 1.

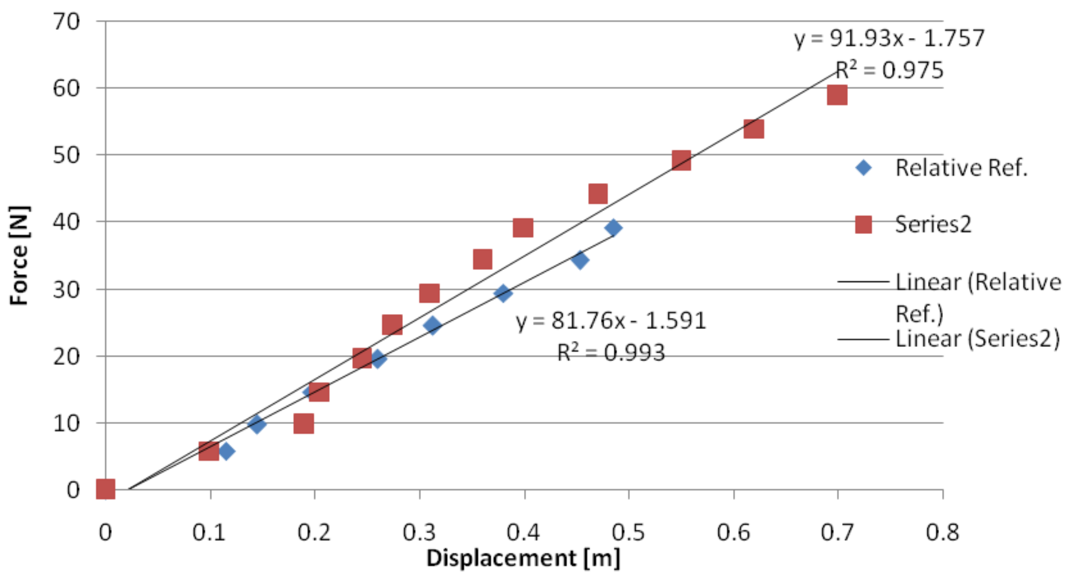

Figure 1: Anchoring Characteristics Kofoed & Antonishen (2008). For the current study, the relative reference setup is valid.

Waves have been measured using 8 separate wave gauges placed in front of and around the device. The PTO used for testing was supplied by the client**.** It involves a disc brake through which the loading provided to the system can be adjusted. This represents the PTO system, which in full scale will include generator. Loading the PTO was done by placing masses in a bucket hanging vertically down from the hand control for the disc break.

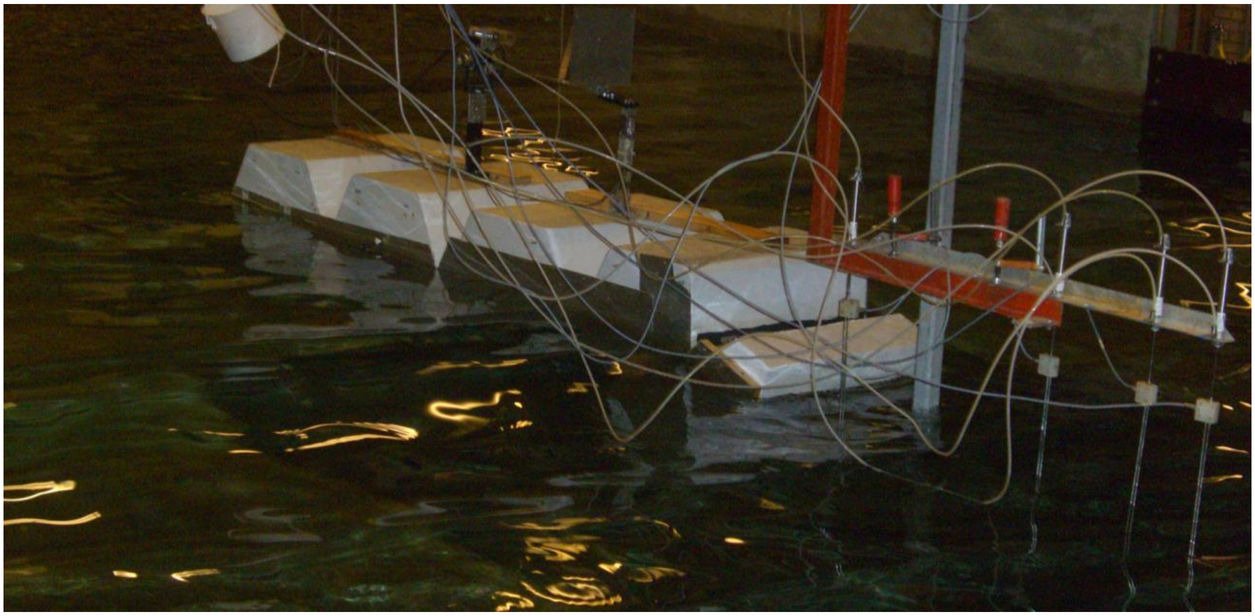

Figure 2: The test model (here Original Device with Inlet mounted) in the wave basin. Wave gauges in front of device used for calculation of incoming waves and their energy contents.

2.1. Power measurement

The test set up for testing is shown in Figure 3. Displacement is measured by a non-contact ultrasonic displacement sensor while force measurements were taken by a ‘bone’ (a strain gauge equipped cantilever beam) installed under the PTO model. Watching the movement of this device it was hypothesized that the vertical force F_v would be very close to 0 because none of the force coming in this direction has any effect on the displacement of the device and therefore it should not be included when calculating power generated. Another thing that was noticed while looking at the results was that the displacement measurement had some noise in it. Due to this, the measured data was filtered (using a low pass filter) to ensure maximum reliability before any power calculations were made. In this case the power calculation was done by taking

$$P = \left[\frac{F_{hm_1} + F_{hm_2}}{2}\right] \cdot \frac{\Delta d}{\Delta t}$$

Where F_{hm_1} is the horizontal force calculated from moment 1 and F_{hm_2} is the horizontal force calculated from moment 2.

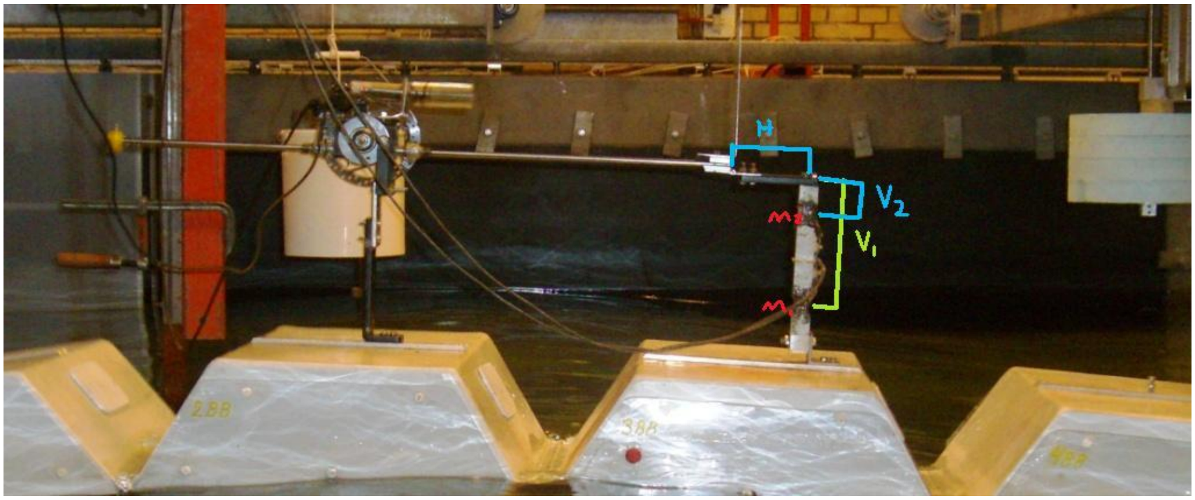

Figure 3: PTO model setup. At left the disc brake providing the PTO load on the system is visible. At the right the 'bone' used for measurement of force is visible.

3. Test Program

The main goals of the phase 2 testing were to increase the efficiency of the device and predict the optimal size of the device in North Sea conditions. The efficiency was optimized by adjusting characteristics of the weight, skirt drafts, and inlet/outlet configurations. The theoretical optimal size has been investigated using a power matrix established through parametric testing of the optimized model this process will be explained in the results section.

Before testing in irregular wave states, the optimal loading conditions on the PTO first had to be found, to find the optimal power production. Optimal loading conditions were found by running 60 second tests in regular wave states similar to the irregular ones that the power production will be later calculated for. The waves chosen for the regular sea states are chosen to maintain the energy contents of the corresponding irregular waves, ie. $H = \frac{H_s}{\sqrt{2}}$ and T = Tp.

The full scale wave states used in this lab testing can be found in Frigaard et al. (2008). For lab testing these states were scaled down using a length scale of 30. Frigaard et al. (2008) also contains probabilities of each wave state occurring. Using the probability of the wave state, the amount of energy per meter in each wave, and the efficiency of the device in the given wave state it is then possible to calculate the average power production per year as well as the overall efficiency.

Sea State	H	T	Sea State	Hs	Tp	Energy Flux	Prob. Occur
	m	s		m	s	W/m	%
R1	.026	1.02	**I1**	.037	1.02	.49	46.8
R2	.052	1.28	**I2**	.073	1.28	2.43	22.6
R3	.078	1.53	**I3**	.110	1.53	6.6	10.8
R4	.104	1.79	**I4**	.147	1.79	13.6	5.1
R5	.130	2.04	**I5**	.183	2.04	24.28	2.4

Table 1: (R) and irregular (I) sea states used in lab (Frigaard et al., 2008). The values given in Table 1 represent the Danish sector of the North Sea, scaled to model scale using a length scale of 1:30.

Table 2 provides an overview of the investigations carried out.

Irregular Wave States 2, 4	Original Device	Original Device Optimized Set Up	New Device Optimized Set Up
Skirt Length Optimization	x		
Inlet/Outlet Testing	x		
Variable Weight Tests		x	x
Horizontal Skirt Var.		x	
Power Matrix		x	
Final Explorations			x

Table 2: Testing scheme for Phase 2.

The testing began with the device as pictured in below in Fig. 5. This is what is referred to as the Original Device in Table 2.

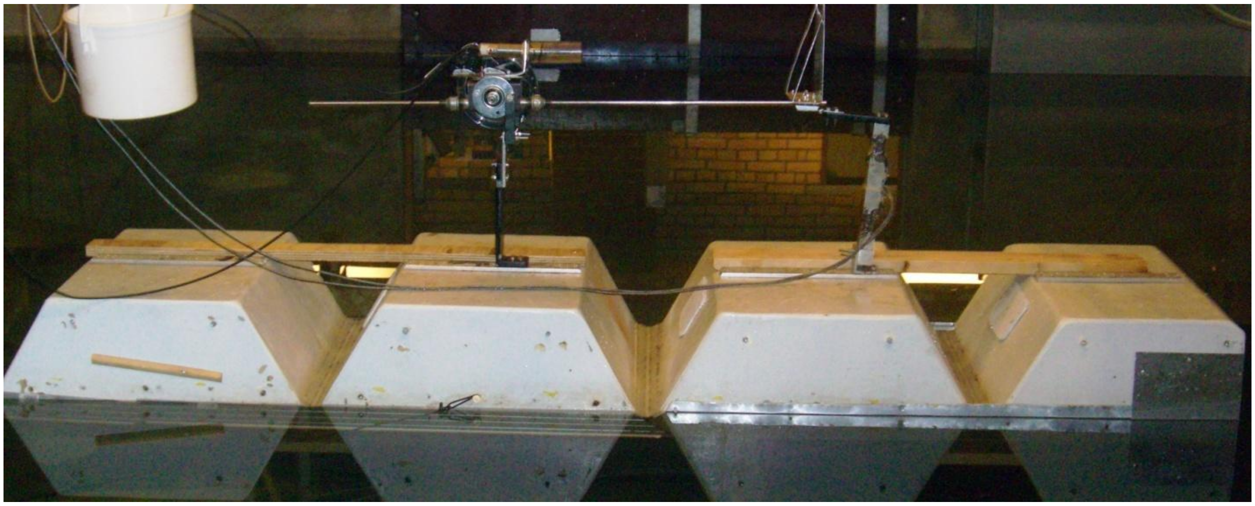

Figure 4: Original setup for Phase 2.

During the current Phase 2 testing, each new result that was found to have a positive effect on efficiency was immediately incorporated into the device set up in order to maximize efficiency. After load optimization, the first tests performed were to determine the optimal skirt length to choose between 10 cm and 00 cm aluminum skirts. Along with finding the optimal vertical length for skirts, the skirts were cut horizontally at three different increments from the front of the device to observe any changes in efficiency this caused. After finding the optimal skirt length and placement, tests were run with many combinations of inlet and outlet devices. The inlet and outlet devices can be seen in Fig. 5.

Figure 5: *Left:* Inlet device. *Right:* Outlet device.

Another issue addressed was the effect of weight on the device. To answer this question, a variety of weight was added in a manner that did not change the center of mass of each floater. Weight tests were also performed where the location of the weight on the Crest Wing did change the center of mass of the floaters. In order to test lighter weights a new and lighter device was built (referred to as New Device). This model can be seen in Fig. 7.

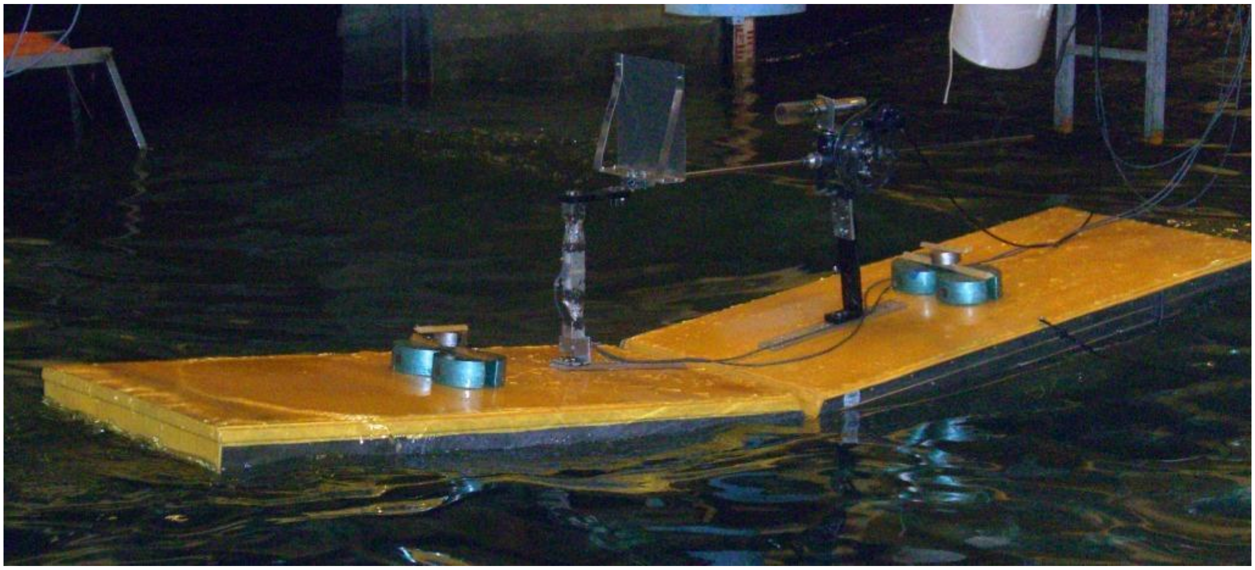

Figure 6: New lighter device with weight added.

Besides a change in weight, this device also originally had a longer front floater (15 cm longer).   Tests were performed with both versions of the new device. After processing the results from all of these tests, the most efficient of all observed set ups was chosen and a power matrix was constructed, based on numerous model tests using a variety of wave states (combinations of Hs and Tp). The power production in the individual tests were turned into efficiencies (non-dimensionalized using available wave energy over the width of the device) and related to the non-dimensional parameters Hs/Lp (wave steepness) and l/Lp (relative device length).

4. Results

Before looking at any results it should be noted that in lower wave states, regular and irregular, the forces and displacements experienced are so low that electronic noise in the measurements can play a relatively large role in the results. In order to ensure good results, some of the signals were run through low pass filters. Very careful attention was given to the filtering of these results to ensure that it was done well and only when needed.

Besides load optimization tests using regular waves, all tests had a duration of 20 minute using irregular tests (corresponding to roughly 1.000 waves). Results in wave states 1 and 2 could not be fully optimized because a low enough load could not be achieved with the available PTO model to find peak production in these states. Because of this, wave states with higher energy waves should be given more attention (results from wave state 4 more reliable than those from waves state 2).

4.1. Skirt Length Optimization

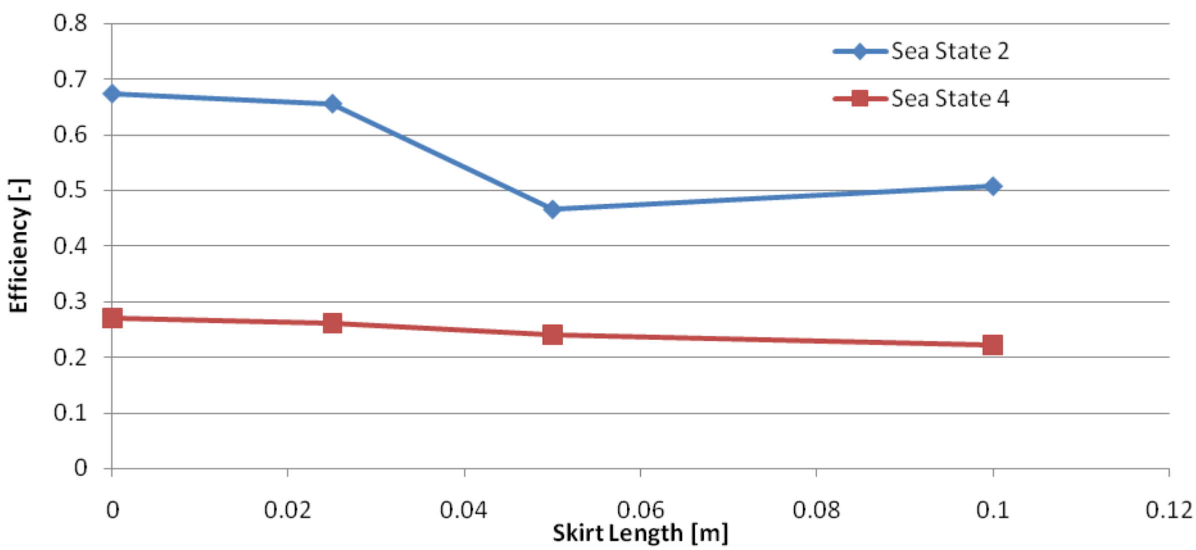

Figure 7: Analysis of Skirt Length vs. Efficiency for the Crest Wing WEC. Data can be found in Appendix A.1.

Fig. 7 further confirms a relationship between skirt length and efficiency that was found in the Phase 1 tests (Kofoed & Antonishen, 2008). The Crest Wing functions best when it has no skirts attached, but only marginally worse with 2.5 cm skirts. The configuration with 2.5 cm skirts were chosen for the further testing, as the skirts play a pivotal role in stabilizing the Crest Wing against lateral movements, which causes power losses.

4.2. Inlet/Outlet Testing

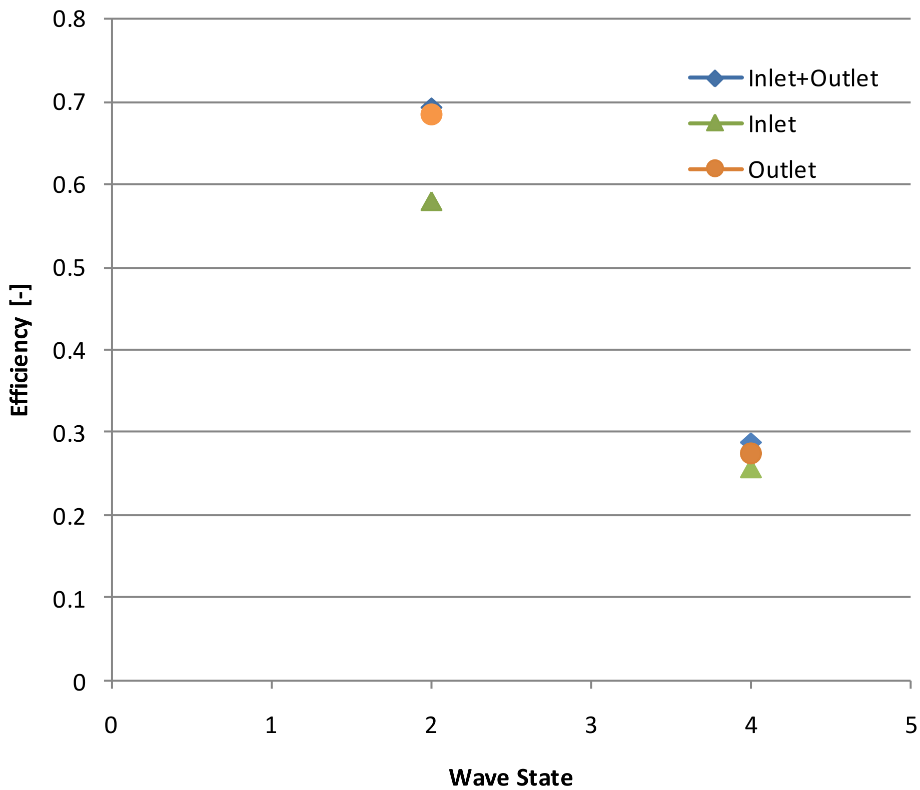

Figure 8: Tests on the effect of inlet and outlet devices on the Crest Wing WEC with 2.5 cm skirts attached. Data can be found in Appendix A.2.

The results given in Fig. 8 clearly show that taking the outlet off of the device always gives a significant drop in efficiency where taking the inlet off results in much less of a change. This data along with qualitative analysis of the forces seen on the inlet and outlet devices lead to the conclusion that the most sensible choice, in terms of what configuration to use in further testing, is using the device with only outlet connected and no inlet.

4.3. Variable Weight Testing

It should be noted that in this section, addition of weights did not change the center of mass of the device or either floater unless otherwise noted.

4.3.1. Original Device

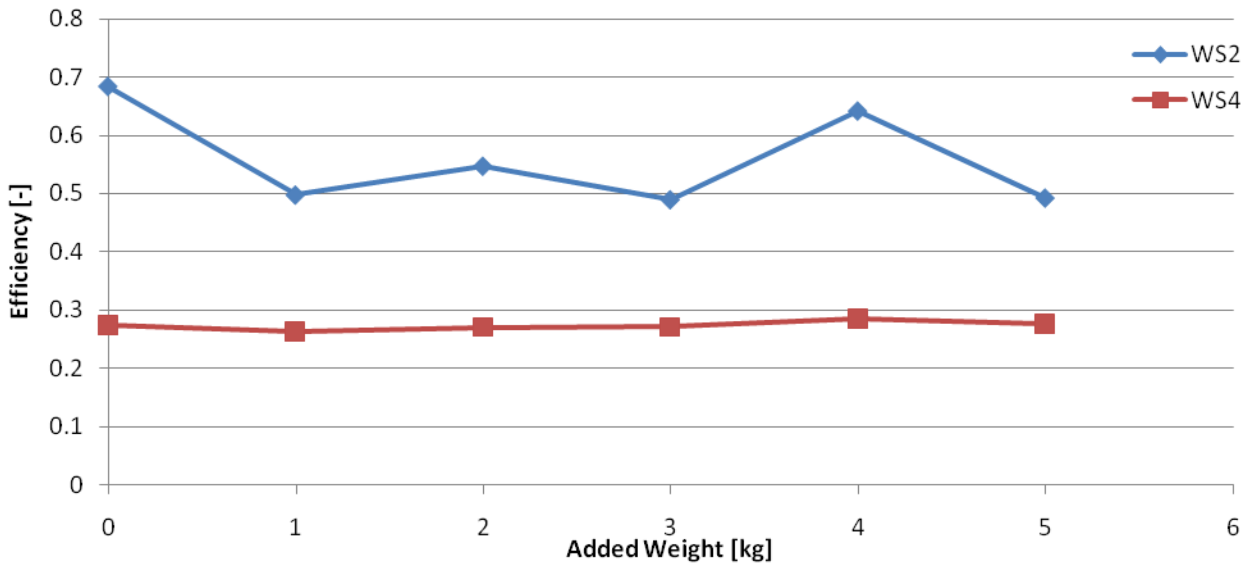

Figure 9: Variable weight test results performed with 2.5 cm skirts and outlet attachment. Data can be found in Appendix A.3

As can be observed in Fig. 11 above, adding variable amounts of weight to the Crest Wing produces results that are stochastic in nature. In wave state 4 the amount of energy in the waves seems to be great enough so that the order of magnitude of the change that was made did not matter. In wave state 2 there is no pattern to be found. The weights obviously have a larger affect here than they do in larger wave states, but the inaccuracies in the PTO have ruined any pattern that could be observed in this case.

4.3.2. New Device

The new model can be seen in Fig. 6. This model is lighter than the older one by 17.4 kilograms and has an extra 15 cm on the front floater but is exactly the same device in other aspects. The results presented in this section can therefore be considered as taking off weight from the old device and expanding the curves in Fig. 11 to the left.

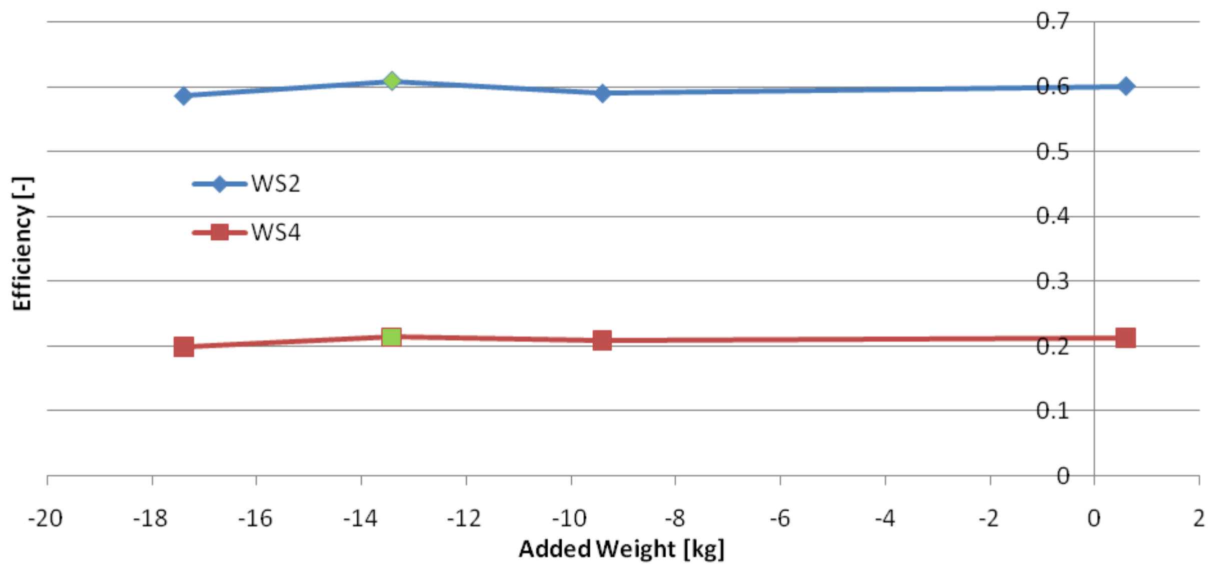

Figure 10: Added weight to the new device. The zero point on this graph represents the weight of the original device used in all previous tests. Data can be found in Appendix A.6

The data in Fig. 10 adds more weight to the argument that adding and subtracting weights of the sizes shown does nothing to the efficiency of the device. The two green data points are special because the weight was added to the outsides of each floater, changing each individual floaters center of mass but leaving the total center of mass unchanged. This change had almost no affect on the device and further exploration is not warranted. The difference between the efficiency in wave state 4 between Fig. 11 and Fig. 12 can be explained by the added 15 cm on the front of the newer prototype

4.4. Horizontal Skirt Variations

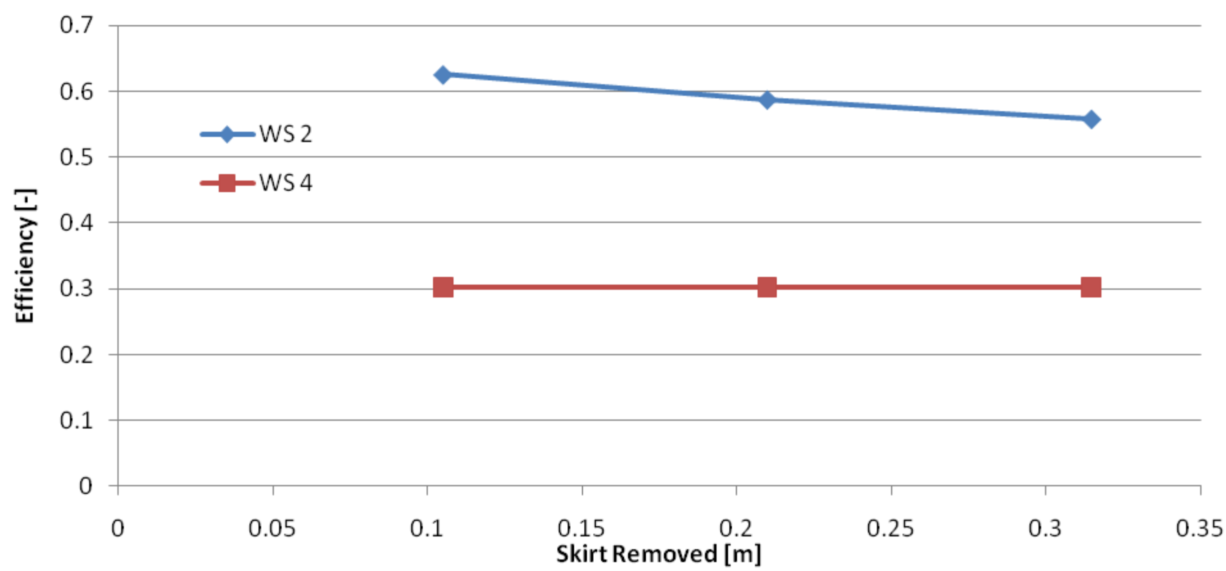

Figure 11: A short exploration of horizontal skirt length on the Crest Wing WEC. Data can be found in Appendix A.5.

The data presented in Fig. 11 suggests that the front part of the skirts does not actually do much for the device as the efficiency did not change when taking them away. Since the skirts do make a difference overall vs. having no skirts, it is safe to say that this difference comes from the rear part of the skirts which were not moved during these tests. It might be useful in the future to cut off sections from the back of the skirts to see what affect this has on efficiency.

4.5 Power Production Tests

Tests in irregular waves corresponding to all 5 wave states (see Table 1) were performed to allow estimation of overall efficiency and yearly power production of the device. Here, as everywhere else in this report, it should be noted that the power talked about is the mechanical power available to the PTO system, and the efficiency is that power normalized by the power in the waves arriving at the width of the device.

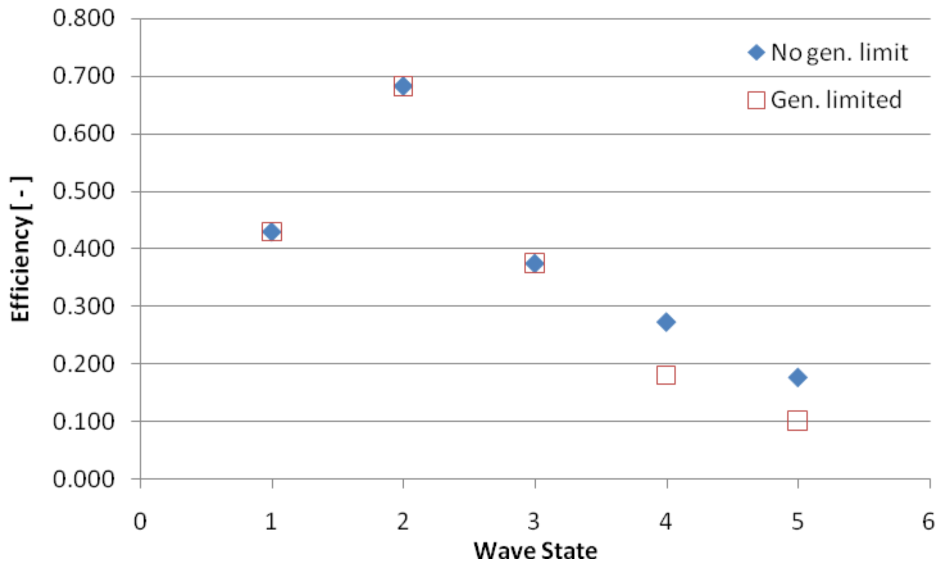

Figure 12: Efficiencies of the Crest Wing WEC (optimal configuration based on tests so far) in the 5 standard wave states. Data can be found in Appendix A.4.

In Fig. 11 the full blue dots represents the actual measured efficiencies, in Table 3 these have been used for calculation of the overall efficiency, as well as corresponding yearly production and load factor. The load factor is here calculated as the ratio between average power production and necessary rated power. In this case the necessary rated power has been set as the highest mean power in the individual waves states. Thus it is assumed *all* fluctuations within the individual irregular waves states are smoothed out by a buffer system, i.e. a flywheel. This is probably not realistic, but in lack of more detailed information this is used as a base for comparisons (in reality a installed generator capacity of at least double of the highest mean power in the individual waves states is not unlikely, but this depends highly on choices made on size of energy buffer in the system).

Wave State	Pwave [kW/m]	Prob [%]	Prob*Pwave [kW/m]	Length scale 1:30, width x length: 18 x 71 m Eff. [-]	Energy prod. [kW/m]	Pgen [kW/m]
1	2.4	46.8	1.12	0.431	0.48	1.03
2	12.0	22.6	2.71	0.684	1.85	8.19
3	32.3	10.8	3.49	0.376	1.31	12.14
4	67.0	5.1	3.42	0.274	0.94	18.37
5	119.7	2.4	2.87	0.178	0.51	21.28
Yearly average [kW/m]			13.61		5.09	
Overall eff. [-]					0.374	
Yearly prod. pr. Crest WingWEC [GWh/y]					0.80	
Max. Pgen [MW]						0.38
Load factor [-]						0.24

Table 3: Crest Wing performance based on model test results, assuming a length scale of 1:30 and no limitations on the installed generator capacity.

In Table 4 the same data is shown, but with a limitation on the installed generator capacity

Wave State	Pwave [kW/m]	Prob [%]	Prob*Pwave [kW/m]	Length scale 1:30, width x length: 18 x 71 m Eff. [-]	Energy prod. [kW/m]	Pgen [kW/m]
1	2.4	46.8	1.12	0.431	0.48	1.03
2	12.0	22.6	2.71	0.684	1.85	8.19
3	32.3	10.8	3.49	0.376	1.31	12.14
4	67.0	5.1	3.42	0.181	0.62	12.14
5	119.7	2.4	2.87	0.101	0.29	12.14
Yearly average [kW/m]			13.61		4.56	
Overall eff. [-]					0.335	
Yearly prod. pr. Crest WingWEC [GWh/y]					0.72	
Max. Pgen [MW]						0.22
Load factor [-]						0.38

Table 4: Crest Wing performance based on model test results, assuming a length scale of 1:30. Installed generator capacity assumed to be limited so it is just able to cope with wave state 3. In waves state 4 and 5 the efficiency is downgraded so this generator capacity is not exceeded.

As it can be seen from these two tables, the limitation on generator capacity results in a decrease in the power production (and efficiency) of 9 % while the load factor is increase by almost 60 %. Thus, it is the ratio between cost of generators and cost of structure that will determine exactly where the limitation on the installed generator capacity should be placed.

4.6. Power Matrix

In the previous section power production potential of the Crest Wing was estimated based on the assumption of a length scale of 1:30 and a certain location in the Danish sector of the North Sea.

In order to enable optimization of the device size to a wider range of locations, a larger range of waves states (combinations of Hs and Tp) have been tested. See Appendix A.7 for detailed results.

The results of these tests (25 in total) are shown in Fig. 12 (red dots) in terms of efficiencies (non-dimensionalized using available wave energy over the width of the device) and related to the non-dimensional parameters Hs/Lp (wave steepness) and l/Lp (relative device length).

An equation was fitted to the points (the plotted surface) to make interpolation of the data possible. Using this is then possible to predict the power production for another scale of the device in a variety of wave states (covered by the performed tests).

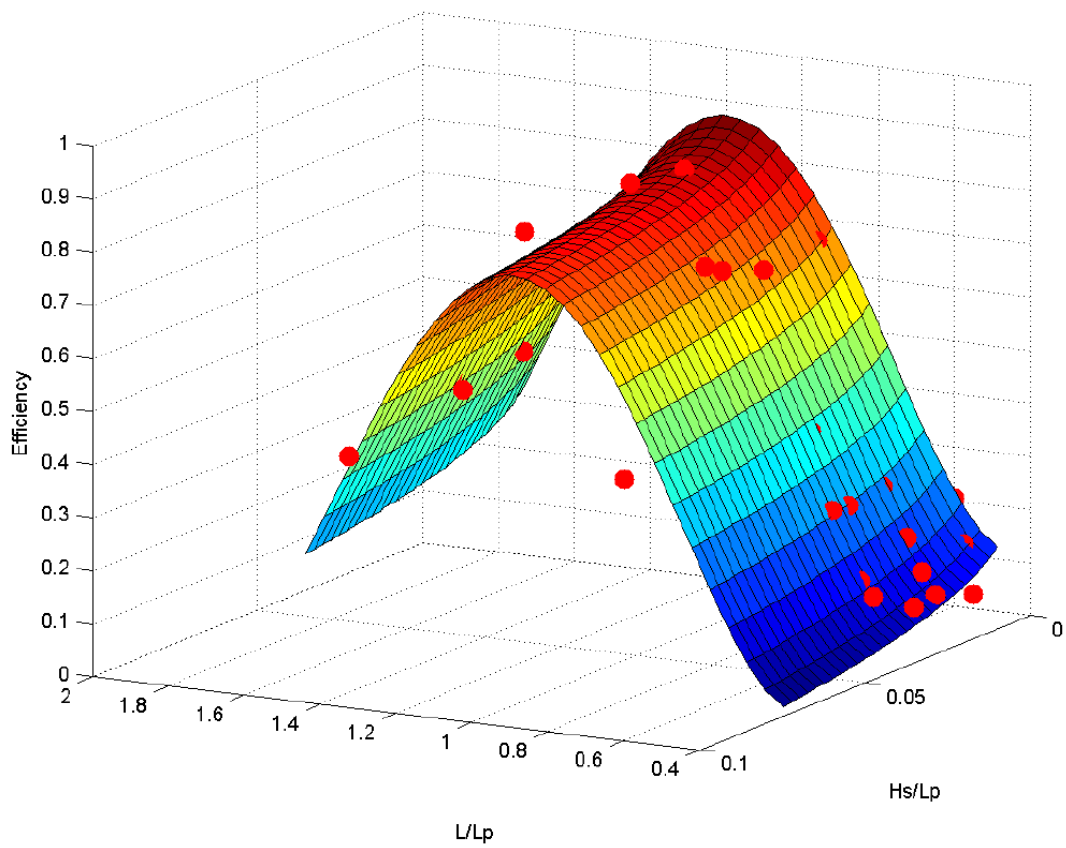

Figure 13: The Surface plot of the equation used to predict efficiency for different lengths of the device. The red points are those points that were actually measured and used to create the plot. Data can be found in Appendix A.7.

From the fitted surface (representing the power matrix of the device) it is clear that the efficiency of the device peaks at a device length equal to the wave length (corresponding to the peak period) or slightly longer (10-20 %). It is also seen that efficiency is higher for smaller wave steepness.

Looking back at the results presented in Table 3 and 4, it is seen that the peak efficiency is not coinciding with the wave condition providing the largest amount of power to the device. Therefore, by choosing different scaling, the length of the device relative to the waves will change, and have an effect on the overall efficiency of the device. In Fig. 14 overall efficiencies of the device for various chosen scales, as function of the corresponding lengths of the device, is shown. The corresponding points in the power matrix are indicated on the surface plot with red dots in Fig. 13.

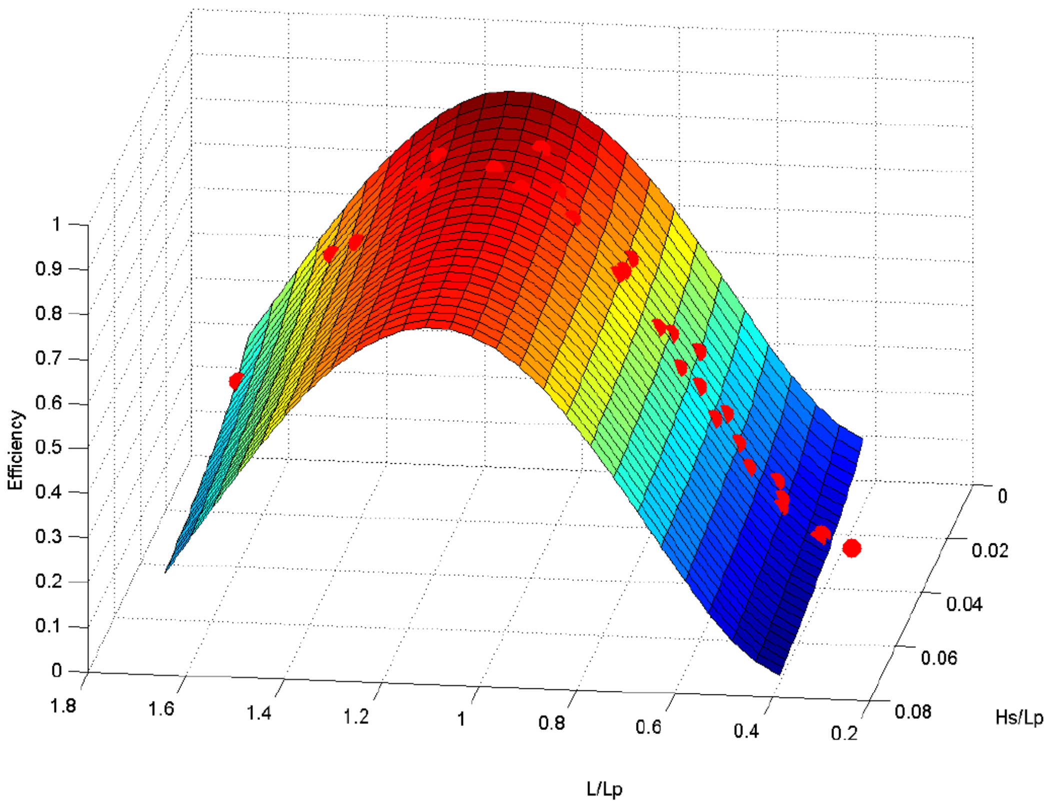

Figure 14: Same surface plot as Fig. 12, but here the red points shows the points that were used for the further analysis (Fig.14-15).

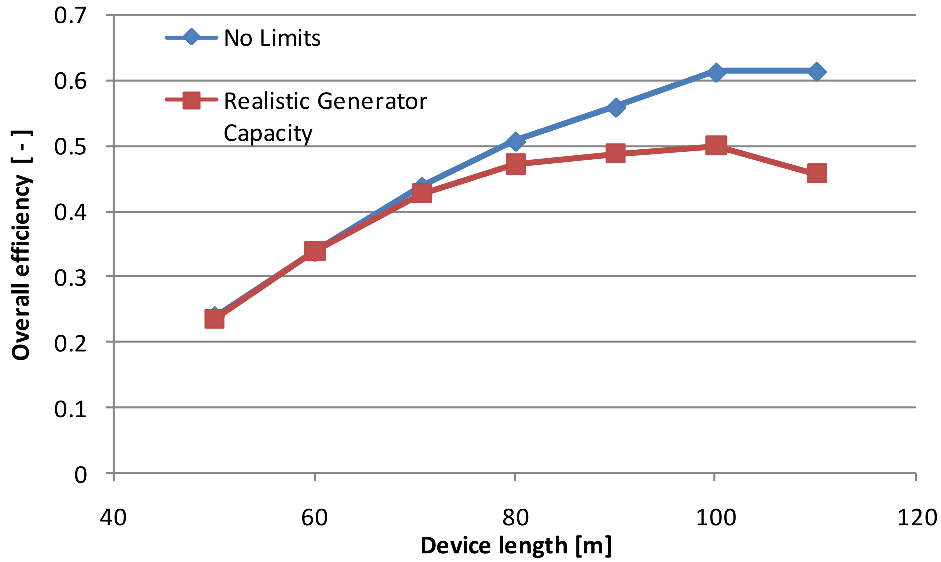

Figure 15: An analysis of device length in full scale vs. power production. The "No Limits" curve is for the case where a limitless generator capacity is assumed and the other case assumes limits on the generator capacity. Data can be found in Appendix A.

In Fig. 14 the blue line corresponds to the situation where no limitations have been put on the maximum power that the system can handle (installed capacity) (situation corresponding to Table 3 in previous section). In this situation it is seen the overall efficiency continues to grow for increasing length of the device, up to a length of approx. 100 m.

The red line corresponds to the situation where the installed capacity is limited to the level necessary to handle all the available power up to and including wave state 3 (situation corresponding to Table 4 in previous section). In this situation it is also seen that the overall efficiency continues to grow for increasing length of the device, up to a length of approx. 100 m, but the growth flattens out already around 80 m.

So the next question is then what is the economically optimal size of the device? When the length of the device is growing, it is simultaneously assumed it is also enlarged in the two other dimensions as well. Thus the volume of the device grows with the length cubes (l^B, B=3). The power production of the device is calculated by multiplying the available power in the waves per meter by the overall efficiency and the width of the device. Thus, if it is assumed the cost of the device follows the volume, then even though an increase in the efficiency is gained by enlarging the device the overall economics will not necessarily improve.

Now, it is not given that the price will be directly proportional to the volume of the device. It is likely that there will be savings due to larger volumes, meaning that B is likely to be less than 3. This is also linked to the fact that not much attention has been given to what structure is actually needed in the device – maybe the height of the structure does not need to be increase proportionally to the length and the width. Therefore an analysis of relative power production per cost as function of device length has been performed for various B values. The results hereof are shown in Fig. 15.

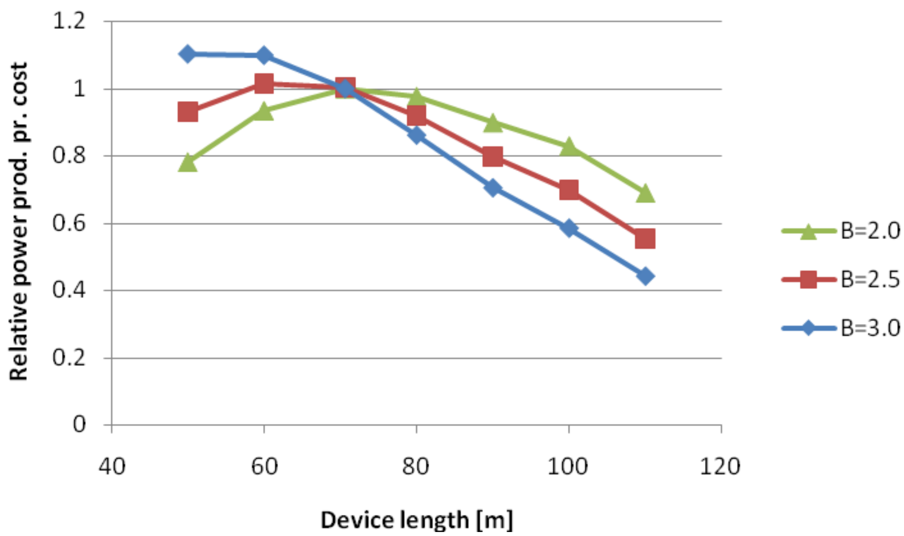

Figure 16: Analysis of relative power production pr. cost as a function of device length for varying B values. This analysis is performed with the above mentioned limitation on generator capacity applied.

From data supplied by the client it is suggested that the costs are directly related to the volume of the device. This means that a B value near 3 is probably the most appropriate. Thus, taking this effect into account the optimal size of device is likely to be in the lower range, i.e. around a device length of 60 m.

4.7. Final Explorations

A few final tests were performed to confirm assumptions that were made or to allow for educated assumptions for the future. The results hereof are shown in Fig. 16.

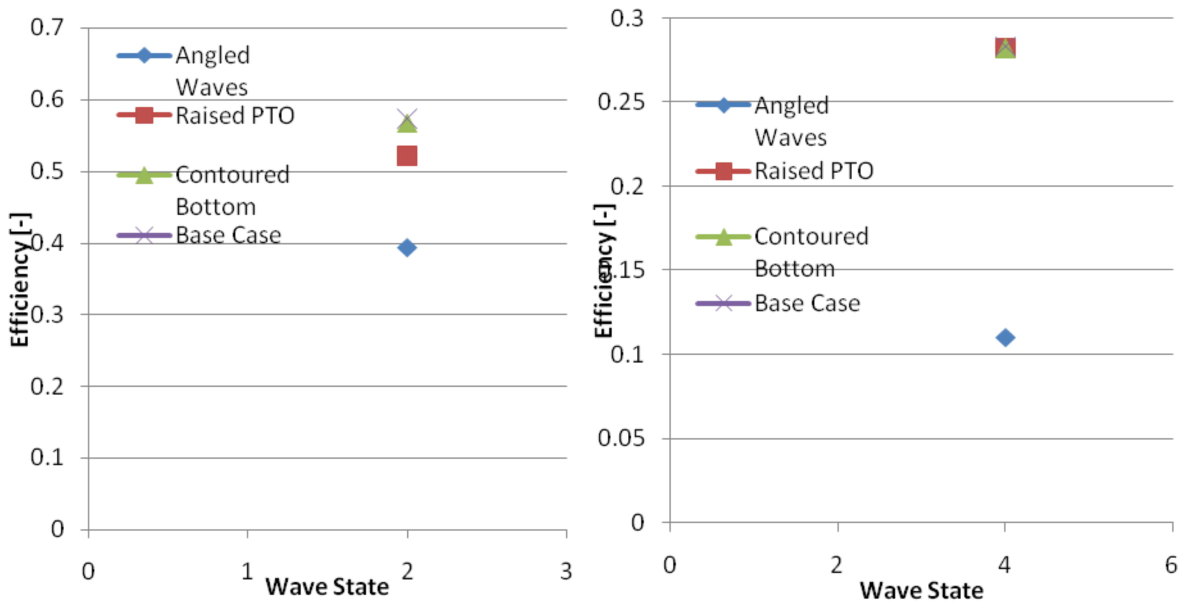

Figure 17: Results for the final tests taken on the Crest Wing WEC in December. Data found in Appendix A.8.

The results above show that changing the contour on the bottom of the device and changing the height of the PTO does little or nothing to efficiency but angling the waves changes it considerably. A large drop in efficiency can be observed in Fig. 16 when the new prototype was tested with irregular waves at a constant angle of 25 degrees from the normal 2D waves. The skirts are useful when considering stability of the device especially in lower wave states but if this is at the cost of efficiency when the wave direction is not aligned with the device then the presence of skirts should be reconsidered. The Crest Wing would benefit from further testing with angled waves and 3D sea states.

5. Conclusions

From the tests, results and analysis carried out in this second phase of testing the following conclusions have been drawn:

- While adding stability, skirt drafts on the Crest Wing also reduce efficiency most notably in 3D wave states. The best balance between stability and efficiency was found using 2.5 cm skirts.
- All inlet devices designed to this point have no effect on efficiency. The outlet device had a significant effect on the Crest Wing's efficiency. In larger scale testing, an outlet should be included.
- Variable weight testing revealed very little to no effect of the weight of the device within the tested parameter range. This is taken as an indication of ratio between weight of the elements of the device and the corresponding cross sectional area in the water plane is far away from a value resulting in a natural frequency being near the ranges of the waves. Thus, natural oscillations of the elements are not achieved. However, it is also considered unlike that this can be achieved for this type of device.
- The tests with variation of the horizontal extent of the skirts indicated that the skirts on the front part of the device do very little to no good for the efficiency of the device.
- Based on power production tests over all the 5 standard waves states showed that in the assumed length scale of 1:30 the device can achieve an overall efficiency (the ratio between the mechanical power available to the PTO system and the power in the waves arriving at the width of the device, averaged over long time, i.e. a year) of 37 %. Introducing a limitation on the installed capacity corresponding to what is necessary to handle the power in wave states up to no. 3 (incl.), reduces this by 9 %, but increases the load factor by 60 %.
- Based on an established non-dimensional power matrix for the device the effect of device size on overall efficiency was analyzed. It was found that increasing the size from the approx. 70 m (corresponding to the assumed length scale of 1:30) to 100-110 m would increase the overall efficiency by approx. 40 % if no limitations were put on the installed capacity. If applying the limitation on the installed capacity corresponding to what is necessary to handle the power in wave states up to no. 3 (incl.), this increase was reduced to approx. 15 %. However, taking device cost into account it seems unlikely that it is economically feasible to increase the length of the device beyond the approx. 70 m. It might even be better to decrease it a little bit, depending on the cost structure.
- Finally, it was found that the device performance was quite sensitive to misalignment between the device and the direction of the waves. A reduction of efficiency of approx. 25 % for an oblique wave attack of 25° was found in wave state 2 and even much larger in wave state 4.

References

Frigaard, Kofoed , and Nielsen: Assessment *of Wave Energy Devices. Best Practice as used in Denmark*. World Renewable Energy Congress (WREC X), Glasgow, UK. July, 2008.

Kofoed, J. P. & Antonishen, M.: *The Crest Wing Wave Energy Device*. DCE Technical Report No. 42. ISSN1901-726X. Dep. of Civil Eng., Aalborg University, Sept. 2008.

Appendix A

Water Depth for all tests: 0.675 m

A.1 Skirt Length Optimization

10 cm Aluminum skirts												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_10_01		2.000	0.073	1.278	0.100	4.000	0.074	3.337	15.757	10.024	1.018	0.508
IF_15_18_40_10_01		4.000	0.147	1.790	0.100	4.000	0.159	23.500	21.064	13.189	3.134	0.222
5 cm Aluminum skirts												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_05_01		2.000	0.073	1.278	0.050	4.000	0.074	3.344	16.029	9.869	0.937	0.467
IF_15_18_40_05_01		4.000	0.147	1.790	0.050	4.000	0.159	23.395	21.183	13.102	3.357	0.239
2.5 cm Aluminum skirts												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_01		2.000	0.073	1.278	0.025	4.000	0.073	3.289	16.429	10.152	1.294	0.656
IF_15_18_40_03_01		4.000	0.147	1.790	0.025	4.000	0.158	23.068	22.383	13.613	3.609	0.261
00 cm Aluminum skirts												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_00_01		2.000	0.073	1.278	0.000	4.000	0.073	3.286	16.685	10.299	1.328	0.674
IF_15_18_40_00_01		4.000	0.147	1.790	0.000	4.000	0.160	23.663	22.722	13.859	3.825	0.269

A.2 Inlet/Outlet Testing

Both Inlet and Outlet Attached												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_11		2.000	0.073	1.278	0.025	4.000	0.073	3.277	17.592	10.453	1.361	0.692
IF_15_18_40_03_11		4.000	0.147	1.790	0.025	4.000	0.161	23.895	24.054	14.710	4.118	0.287
Inlet Attached, No Outlet												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_21		2.000	0.073	1.278	0.025	4.000	0.072	3.211	16.639	9.967	1.115	0.579
IF_15_18_40_03_21		4.000	0.147	1.790	0.025	4.000	0.161	23.980	24.567	14.914	3.696	0.257
Outlet Attached, No Inlet												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave cond.	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_31		2.000	0.073	1.278	0.025	4.000	0.075	3.462	18.233	11.186	1.421	0.684
IF_15_18_40_03_31		4.000	0.147	1.790	0.025	4.000	0.164	25.005	25.346	15.718	4.113	0.274

A.3 Original Device Variable Weight Testing, Outlet Attached-No Inlet

4 Kilos Added to each floater												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_41		2.000	0.073	1.278	0.025	4.000	0.074	3.310	16.117	12.167	1.274	0.642
IF_15_18_40_03_41		4.000	0.147	1.790	0.025	4.000	0.159	23.305	25.681	18.414	3.992	0.285
2 Kilos Added to each floater												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_51		2.000	0.073	1.278	0.025	4.000	0.074	3.355	16.076	13.180	1.101	0.547
IF_15_18_40_03_51		4.000	0.147	1.790	0.025	4.000	0.160	23.783	26.805	20.237	3.868	0.271
1 Kilo Added to each floater												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_61		2.000	0.073	1.278	0.025	4.000	0.074	3.351	16.557	14.293	1.000	0.497
IF_15_18_40_03_61		4.000	0.147	1.790	0.025	4.000	0.160	23.635	28.344	22.160	3.735	0.263
3 Kilos Added to each floater												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_71		2.000	0.073	1.278	0.025	4.000	0.073	3.313	17.193	15.131	0.973	0.489
IF_15_18_40_03_71		4.000	0.147	1.790	0.025	4.000	0.160	23.690	29.230	23.170	3.854	0.271
5 Kilos Added to each floater												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_81		2.000	0.073	1.278	0.025	4.000	0.075	3.425	17.377	15.859	1.012	0.492
IF_15_18_40_03_81		4.000	0.147	1.790	0.025	4.000	0.160	23.738	30.064	24.076	3.947	0.277

A.4 Irregular Tests, Outlet Attached-No Inlet, No Weight Added

Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_03_10_40_03_31		1.000	0.037	1.022	0.025	4.000	0.030	0.404	6.400	5.184	0.104	0.431
IF_05_13_40_03_31		2.000	0.073	1.278	0.025	4.000	0.075	3.462	18.233	11.186	1.421	0.684
IF_11_15_40_03_31		3.000	0.110	1.530	0.025	4.000	0.120	11.345	26.132	22.014	2.558	0.376
IF_15_18_40_03_31		4.000	0.147	1.790	0.025	4.000	0.164	25.005	25.346	15.718	4.113	0.274
IF_18_20_45_03_31		5.000	0.183	2.045	0.025	4.500	0.197	39.445	44.918	35.767	4.208	0.178
IF_18_20_50_03_31		5.000	0.183	2.045	0.025	5.000	0.196	39.080	55.163	42.359	3.915	0.167

A.5 Horizontal Skirt Variations, Outlet Attached-No Inlet

Front Skirts cut by 10.5 Cm												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_91		2.000	0.073	1.278	0.025	4.000	0.072	3.188	16.059	12.186	1.196	0.625
IF_15_18_40_03_91		4.000	0.147	1.790	0.025	4.000	0.157	22.855	26.016	19.125	4.145	0.302
Front Skirts cut by 21 Cm												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_A1		2.000	0.073	1.278	0.025	4.000	0.072	3.199	16.602	13.879	1.127	0.587
IF_15_18_40_03_A1		4.000	0.147	1.790	0.025	4.000	0.157	22.853	27.551	20.924	4.157	0.303
Front Skirts cut by 31.5 Cm												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_40_03_B1		2.000	0.073	1.278	0.025	4.000	0.072	3.191	16.958	14.317	1.067	0.558
IF_15_18_40_03_B1		4.000	0.147	1.790	0.025	4.000	0.158	23.045	28.162	22.038	4.187	0.303

A.6 New Device Weight Tests, Outlet-No Inlet

0 Kilos Added												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_C1		2.000	0.073	1.278	0.025	0.000	0.069	2.989	10.795	6.824	1.050	0.585
IF_15_18_40_03_C1		4.000	0.147	1.790	0.025	4.000	0.156	22.698	20.247	14.035	2.712	0.199
8 Kilos Added, no change to Center of Mass												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_D1		2.000	0.073	1.278	0.025	0.000	0.070	3.062	10.952	6.972	1.082	0.589
IF_15_18_40_03_D1		4.000	0.147	1.790	0.025	4.000	0.154	22.130	20.462	14.248	2.780	0.209
18 Kilos Added, no change to Center of Mass												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_E1		2.000	0.073	1.278	0.025	0.000	0.071	3.079	10.888	6.845	1.109	0.600
IF_15_18_40_03_E1		4.000	0.147	1.790	0.025	4.000	0.158	23.020	20.829	14.627	2.936	0.213
4 Kilos Added, Outer edges, change in Center of Mass of each individual floater.												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_F1		2.000	0.073	1.278	0.025	0.000	0.070	2.985	11.288	7.087	1.089	0.608
IF_15_18_40_03_F1		4.000	0.147	1.790	0.025	4.000	0.156	22.425	21.379	15.372	2.882	0.214
IF_15_18_	comparis	4.000	0.147	1.790	0.025	4.500	0.156	22.520	29.814	23.827	3.007	0.223

A.7 Power Matrix Testing, Outlet-No Inlet

Filename	Rem.	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_04_10_00_03_31		0.040	1.000	0.025	0.000	0.038	0.657	5.952	4.481	0.182	0.463
IF_04_14_00_03_31		0.040	1.400	0.025	0.000	0.039	1.104	8.399	5.625	0.465	0.701
IF_04_20_00_03_31		0.040	2.000	0.025	0.000	0.045	2.054	7.586	5.227	0.291	0.236
IF_06_08_00_03_31		0.060	0.800	0.025	0.000	0.052	1.004	7.053	5.056	0.210	0.348
IF_06_12_00_03_31		0.060	1.200	0.025	0.000	0.056	1.759	10.459	6.819	0.893	0.846
IF_06_16_00_03_31		0.060	1.600	0.025	0.000	0.068	3.908	11.319	7.210	0.971	0.414
IF_06_22_00_03_31		0.060	2.200	0.025	0.000	0.070	5.272	9.324	6.320	0.518	0.164
IF_08_10_00_03_31		0.080	1.000	0.025	0.000	0.072	2.374	9.409	6.210	0.676	0.475
IF_08_14_00_03_31		0.080	1.400	0.025	0.000	0.082	4.760	13.728	7.779	1.961	0.687
IF_08_18_00_03_31		0.080	1.800	0.025	0.000	0.091	7.721	12.511	7.306	1.314	0.284
IF_08_24_00_03_31		0.080	2.400	0.025	0.000	0.090	9.166	16.892	11.582	0.436	0.079
IF_10_12_00_03_31		0.100	1.200	0.025	0.000	0.091	4.767	14.228	8.149	2.459	0.860
IF_10_16_00_03_31		0.100	1.600	0.025	0.000	0.111	10.338	14.757	8.027	2.514	0.405
IF_10_20_00_03_31		0.100	2.000	0.025	0.000	0.111	12.518	13.166	7.478	1.494	0.199
IF_12_14_40_03_31		0.120	1.400	0.025	4.000	0.117	9.819	20.963	15.753	4.222	0.717
IF_12_18_40_03_31		0.120	1.800	0.025	4.000	0.133	16.455	20.879	15.901	2.715	0.275
IF_12_22_40_03_31		0.120	2.200	0.025	4.000	0.134	19.565	18.908	14.603	1.690	0.144
IF_14_14_40_03_31		0.140	1.400	0.025	4.000	0.132	12.535	25.264	20.686	5.552	0.738
IF_14_18_40_03_31		0.140	1.800	0.025	4.000	0.151	21.365	28.707	23.820	3.544	0.276
IF_14_24_40_03_31		0.140	2.400	0.025	4.000	0.156	27.240	27.087	22.261	1.732	0.106
IF_16_16_45_03_31		0.160	1.600	0.025	4.500	0.168	23.700	44.382	37.926	5.136	0.361
IF_16_20_45_03_31		0.160	2.000	0.025	4.500	0.175	30.555	44.188	35.793	2.774	0.151
IF_18_24_45_03_31		0.180	2.400	0.025	4.500	0.192	40.888	45.764	35.806	2.441	0.099
IF_20_18_50_03_31		0.200	1.800	0.025	5.000	0.208	40.183	67.097	53.069	4.749	0.197
IF_20_22_45_03_31		0.200	2.200	0.025	4.500	0.209	46.525	56.016	44.496	3.731	0.134

A.8 Final Explorations

2.5 cm skirts, Outlet Attached- No Inlet												
New Device cut to size of old device - Angled Waves (25 degrees from normal)												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_V1		2.000	0.073	1.278	0.025	0.000	0.066	2.946	9.932	6.196	0.695	0.393
IF_15_18_40_03_V1		4.000	0.147	1.790	0.025	4.000	0.160	24.143	21.501	18.650	1.596	0.110
2.5 cm skirts, Outlet Attached- No Inlet												
New Device cut to size of old device - 12 cm Raised PTO (reproducing other model again)												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_Y1		2.000	0.073	1.278	0.025	0.000	0.071	3.024	10.542	7.035	0.946	0.521
IF_15_18_40_03_Y1		4.000	0.147	1.790	0.025	4.000	0.138	17.385	22.655	19.828	2.946	0.282
2.5 cm skirts, Outlet Attached- No Inlet												
New Device cut to size of old device - Wood pattern on Bottom												
Irregular Tests -- 20 minutes												
Filename	Rem.	Wave con	Inp. H [m]	Inp. T [s]	Skirt draft [m]	Load [kg]	Meas. H [m]	P_wave [W]	F_h Mean [N]	F_h StDev [N]	P [W]	Eff. [-]
IF_05_13_00_03_X1		2.000	0.073	1.278	0.025	0.000	0.071	3.023	11.369	6.930	1.028	0.567
IF_15_18_40_03_X1		4.000	0.147	1.790	0.025	4.000	0.138	17.405	25.126	21.536	2.948	0.282