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Results of an Experimental Study of the Langlee Wave Energy Converter

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ABSTRACT

This paper presents the results of the first experimental study of the Langlee wave energy converter (WEC), a semi-submerged oscillating wave surge converter. Its design extracts the energy from the surge motion of the waves through two pairs of working flaps, called water wings, which are placed symmetrically opposing each other. The results predict the power production performance of the Langlee WEC model for two locations of interest, a generic offshore location in the Danish part of the North Sea and at Horns Rev 1, a Danish offshore wind farm.

KEY WORDS: Wave energy converters, Langlee, predicted power production, experimental laboratory testing, oscillating wave surge converter, hydraulic behaviour.

NOMENCLATURE

Hs = Significant wave height
ND perf. = Non-dimensional performance
Pgen = Generated power
Prob = Probability of occurrence
PTO = Power take-off
Pwave = Wave power
S = Directional spreading parameter
Tp = Wave peak period
WEC = Wave energy converter

INTRODUCTION

The Langlee wave energy converter (WEC) project was first conceived in 2005 and is currently being developed by the team of Julius Espedal under the name of Langlee Wave Power, Norway. The Langlee WEC is more specifically known, as an oscillating wave surge converter as it extracts the kinetic energy available in the orbitally moving water particles, excited by the waves, through a number of hinged flaps positioned just under the surface of the water. This device is unique from the rest of the oscillating wave surge converters, due to it having a pair of working flaps that are placed symmetrically opposing each other, all mounted on a moored floating reference frame – a semi-submerged steel structure. At suitable wavelengths, the symmetry will help to minimize the forces on the structure and moorings while the flaps should complement each other to extract the maximum amount of energy.

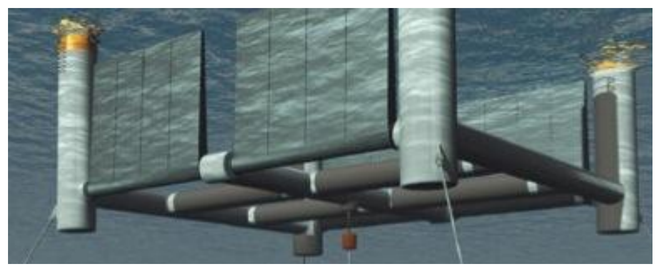

Fig.1: Underwater artist impression of the Langlee WEC

The principle aim of this work is to investigate the power conversion capabilities of the device under various wave conditions and to analyze key design parameters, such as its structural behaviour under wave interaction, the effect of damping plates and the mooring system.
Therefore, a 1.25m x 1.25m (in horizontal plane) reduced-size model of the Langlee WEC has been tested in the deep wave basin at the Department of Civil Engineering of Aalborg University, Denmark.

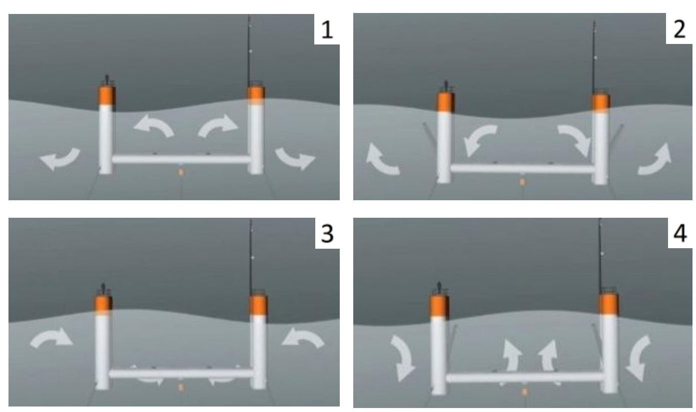

Fig. 2: Side view illustration of the working principle of the WEC

As for a full-scale Langlee WEC, each water wing of the model is equipped with its own power take-off (PTO) system, which is located in the closest vertical corner column. The model's PTO system however consists of a load-adaptable friction wagon mounted on a rail, a potentiometer to measure the displacement of the water wings and a force transducer, in order to record the transmitted force through the water wings. From the angular rotation of the potentiometer, the displacement of the wagon was calculated. Besides the PTO system, 12 more sensors were used to record data: six wave gauges, three ultrasonic sensors that recorded the surge, heave and pitch motions of the model and three load cells measuring the mooring forces.

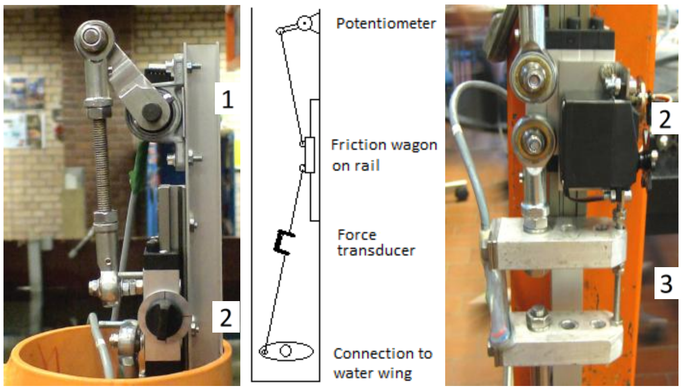

Fig.3: View of the PTO system with potentiometer (1), load-adjustable friction wagon (2) and force transducer (3)

Initial tests were performed with monochromatic waves in order to reveal some general trends of the device; however, all remaining tests were defined as irregular 2D waves, following a JONSWAP spectra. The regular wave tests were done over a time period of 3 minutes, corresponding to 90 – 250 waves, while 30 minutes tests were used with irregular waves, corresponding to 900 – 2500 waves. The model was tested for the seven wave states, to analyse its power generating capabilities. The investigation on the effect of alterations on the structure or on the general setup was done by comparing each test to a common reference test and setup. This reference was repeated before every alteration study. The tested wave states are based on different scaling ratios of the wave climates found in two locations of interest, Horns Rev 1, a Danish offshore wind farm (Table 2), and a generic offshore location in the Danish part of the North Sea (Table 3). The tested wave states in the basin have wave heights (Hs) ranging from 0.04m until 0.11m and wave periods (Tp) from 0.7 s till 2.0s, while the wave states of the Horns Rev 1 location have Hs between 0.5 and 3.5m and Tp from 2.8 till 9.0s and in the Danish North Sea Hs ranges from 1 to 5m and Tp from 5.6 till 11.2s (Kofoed & Frigaard, 2009).

Table 1: Wave height and wave period of the tested wave states

Wave state	1	2	3	4	5	6	7
Hs [m]	0.04	0.04	0.04	0.05	0.07	0.09	0.11
Tp [s]	0.7	1	1.15	1.3	1.5	1.75	2

The lower limit in wave height of the 0.75m deep wave basin was set at 0.04m in order to keep the range of measurements appropriate.

TEST METHODS

The tests of the study can be divided in three main parts. The first part intends to identify the prototype's general behaviour, its main influential parameters and the optimal load setting. Then tests were performed in all the seven wave states in order to be able to predict the performance of the device for different scaling ratios at two offshore locations. The last part of the study addressed the impact of alterations on the model or on the general testing conditions.

All the tests have been performed using the optimal load setting that has been identified during the initial tests for both rows of water wings. The performance results are based on the data of the water wings located on the left of the device, facing the waves, as only they were equipped with force transducers. The mooring setup consisted of 3 rubber ropes, 2x2.2m at the front and 1x1.3m at the back, which had a stiffness coefficient of 38.6N/m and the model setup had a stiffness coefficient for the total mooring setup of 35.1N/m. All the data has been recorded and processed in WaveLab 3.3, developed at Aalborg University.

General Characteristics

Performance Dependency on Wave Period and Wave Height

It has been very useful to know the dependency of the performance of the device towards the wave height and wave period. In order to evaluate these dependencies, the performance of the model has been measured for various wave periods, while the wave height was kept constant at 0.06m. A comparable test was realized in which the wave period constant was maintained at 1.3 seconds, while the wave height was varied. These tests were repeated in irregular waves, after the regular waves, and for different load settings, in order to determine which gives the best overall performance. The corresponding Fig. 6 and 7 give these results for various load settings in regular waves.

Response Motion of the Structure

Tests were performed to identify the natural frequency of motion of the structure as well as the transfer functions from regular and irregular waves to the heave, surge and pitch motion of the Langlee model.

The natural frequency of oscillation in heave, surge and pitch was assessed by applying a force impulse on the structure, which causd the structure oscillate only in the desired degree of freedom. This decaying motion, oscillating at a constant frequency, was captured on video. The oscillations were afterwards identified and timed.

The transfer functions of the heave, surge and pitch motion are calculated the regular and irregular waves. Testing with monochromatic waves makes it possible to analyze the device for just one well-known source of excitation, providing a useful reference. This was done for eight different wave conditions, in the range from Hs and Tp of 0.06m and 0.6s to 0.16m and 2.3s waves. Then similar tests were performed with irregular waves in order to see if the same response is predominant or if the reaction of the device would vary under the influence of a wave spectrum. For the test involving irregular waves, the transfer function is given for different wave states depending on the quality of the data. Their name tags refer to the wave conditions and the date of the test, e.g.07.15 090710 means that the test was ran on the 10 July 2009 with Hs of 0.07m and Tp of 1.5s.

The transfer function of the heave, surge and pitch motion in regular waves was calculated by taking the square values of the division of the average heave, surge or pitch motion by the wave height. The transfer functions of the irregular waves were taken from the variance spectrum by frequency domain analysis, calculated in Wavelab 3.3. All the spectral density values are given in [$s.m^2$] except for the pitch spectral density values, which are in [$s.rad^2$]. The transfer functions were obtained by dividing the spectral density value of the motion at a precise frequency (Response) by the spectral density value of the incident wave of all the matching frequencies (Input).

Performance Analysis

Non-dimensional Performance of the Langlee WEC

The non-dimensional performance of the model is given for the seven wave states using the optimal load setting, which was identified to yield the highest overall non-dimensional performance. The non-dimensional performance corresponds to the measured absorbed power by all the water wings divided by the available wave power for the width of a pair of water wings. As the performance of the device was found to be the most dependent on the wave period, the performance has been plotted against this variable.

Predicted Performance for Horns Rev 1 and Danish North Sea

Based on the non-dimensional performance of the device in the seven tested wave states, the performance of a full-scale device has been estimated by interpolation. The estimated performance is given for two different scaling ratios for the wave conditions found at the Horns Rev 1 location (water depth of 10m) and for three different scaling ratios for a standard Danish North Sea (water depth of 30m) as well as the estimated yearly generated power and load factor.

The 'Power production', stated in the summarizing performance table 5 and 6, refers to the average mechanical power available to the PTO system in a wave state over time and corresponds to multiplying the corresponding non-dimensional performance by the probability of occurrence and average wave power of that particular wave state. So the yearly average power production is the total of all the individual wave state power productions. 'The Power generated' is the average generated power in a particular wave state and corresponds to the non-dimensional performance multiplied by the average available wave power in that wave state. In order to further summarize these results, the yearly-average generating power of the device, the overall non-dimensional performance, the amount of yearly-produced power, the maximum generating power and the load factor is calculated. The 'load factor' represents the ratio between the yearly-average generating power to the generating power in the largest wave state, which is assumed to be the rated power.

Table 2: Wave states representing Horns Rev 1 (Sørensen et al., 2005)

Real sea conditions					Scale 1:20		Scale 1:30	
Wave State	Hs [m]	Tp [s]	Wave power [kW/m]	Prob. [%]	Hs [m]	Tp [s]	Hs [m]	Tp [s]
1	0.5	2.8	0.3	21.3	0.03	0.63	0.02	0.51
2	1.0	5.5	2.4	34.2	0.05	1.23	0.03	1.00
3	1.5	6.2	6.0	21.2	0.08	1.39	0.05	1.13
4	2.0	6.9	11.8	12.9	0.10	1.54	0.07	1.26
5	2.5	7.6	20.2	6.6	0.13	1.70	0.08	1.39
6	3.0	8.3	31.8	3.3	0.15	1.86	0.10	1.52
7	3.5	9.0	46.9	0.6	0.18	2.01	0.12	1.64

Table 3: Wave conditions characterising the Danish North Sea (Kofoed & Frigaard, 2008)

Real sea conditions					Scale 1:20		Scale 1:30	
Wave State	Hs [m]	Tp [s]	Wave power [kW/m]	Prob [%]	Hs [m]	Tp [s]	Hs [m]	Tp [s]
1	1.0	5.6	2.4	46.8	0.05	1.25	0.03	1.02
2	2.0	7.0	12.0	22.6	0.10	1.57	0.07	1.28
3	3.0	8.4	32.3	10.8	0.15	1.88	0.10	1.53
4	4.0	9.8	67.0	5.1	0.20	2.19	0.13	1.79
5	5.0	11.2	119.7	2.4	0.25	2.50	0.17	2.04

Effect on the Performance of Model or Setup Alterations

The effects of several alterations on the model and on the test setup have rather been promptly investigated in order to have a concise impression about their magnitude of influence. These results are meant to give an insight into possible improvements concerning design, implementation and setup conditions. In this part of the study, the test, in which a modification was made to the model or setup, was directly followed by a reference test, without any modifications, in order to perceive only the effect of that specific alteration.

Fixed Structure

By fixing the structure to the sea bed, we could find a possible upper limit of performance of the device with these settings (e.g. water wing design, load setting and all the other parameters). It is expected that the movement of the frame would absorb a part of the wave energy and reduce the rotational movement of the water wings as their rotation point would move laterally with them. Therefore, greater motions might consequently result in lower non-dimensional performances.
The device was tested at two irregular wave conditions, 0.04m – 1.15s and 0.07m – 1.5s, and compared to results obtained with the reference slack-moored setup.

Damping Plates

The damping plates consisted of circular plates mounted below the bottom of each column. They are intended to act as "added mass", thereby reducing the heave and pitch motion of the device and possibly improving the performance.

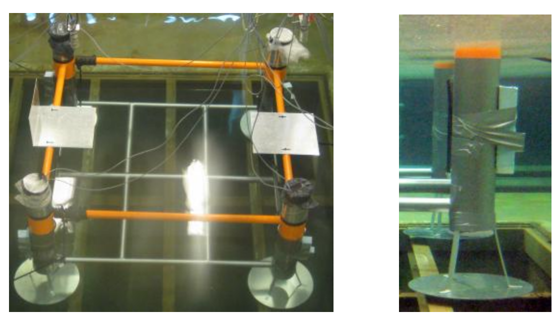

Fig.4: Top and side view of the Langlee model with damping plates

The additional weight, coming from the damping plates, on the model was compensated by adding foam, as can be noticed on Fig. 4. The tests were performed for three different wave conditions, respectively 0.04m – 1.15s, 0.07m – 1.5s and 0.09m – 1.75s. Only during these tests, the depth of the wave basin was increased in order to avoid any side effects, such as suction in between the damping plates and the bottom of the basin. The reference test was made under the same conditions but without the plates in order to analyse only their effect and to cancel out the influence of the 1.5m deep pit on the wave characteristics.

Oblique Waves

A few tests were performed with 0.05m – 1.3s irregular waves to find out how the direction of the incident waves would affect the performance of the Langlee model. This investigation could give some insight into the mooring design, i.e. whether it should have a fixed direction or be allowed to rotate to face the predominant direction of incoming waves.

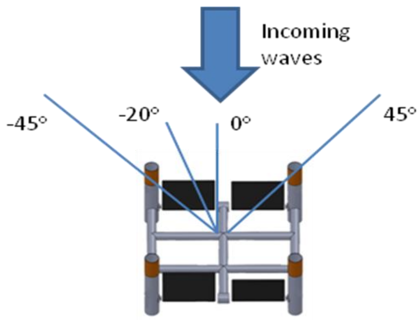

Fig.5: Impression of the tested angles of attack for oblique waves

The device was tested at 2 different angles (20° and 45°), when rotated to the right side and 1 angle (45°), when rotated the left. This is illustrated in Fig. 5. The results are compared to a reference test performed at 0°. The reason the device was tested in both directions is that the water wings with the PTO units where only installed on one side (left relative the incoming wave) of the device. It was also expected that the power production would be affected by what side the water wings where, when rotated around. The water wings further away would produce less power, due to the fact that the other water wings and the columns would be shielding them from the incident waves.

Waves with Directional Spreading (3D Waves)

Real offshore waves are rarely purely long crested (2D); this is a convenient simplification applied in the laboratory. A more realistic representation of the real offshore wave conditions can be made using 3D waves, which include the directional spreading of the waves, quantified by the S factor. To investigate the effect of the distribution of the wave energy over various frequencies and directions on the performance of the device, corresponding tests were performed for two wave states, 0.04m – 1.15s and 0.07m – 1.5s. Each wave state was tested for 2 spreading settings, an S parameter of 2 (maximum spreading) and 10 (limited spreading), and compared with the corresponding 2D irregular wave state as reference. In the resulting graph (Fig.19), the S parameter of 10 corresponds to a value of 1 as it is an intermediate state between purely 2D and a full 3D wave state.

RESULTS AND DISCUSSION

General Characteristics

Performance Dependency on the Wave Period

The results of the corresponding test confirm that the performance of the model is closely linked to the wave period. A noticeable peak in its performance appears at a wave period of around 1.3 seconds, corresponding to a wavelength of 2.52m. This is twice the length of the model and distance between the water wings, and therefore makes the water wings move simultaneous in opposite direction. This gives a significant counterforce to the induced force of the water wings and hence considerably enhances the performance. This wave period will be referred to as the wave period of peak performance.

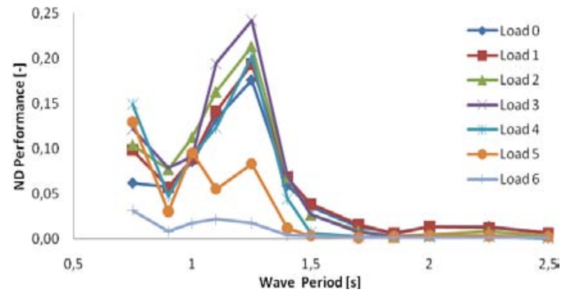

Fig.6: Evaluation of the dependency of the model towards wave period in regular waves

On the other hand, it is noticeable that the performance drops more significantly when the wave period exceeds the period of peak performance than for slightly shorter periods.

Performance Dependency on the Wave Height

Contrary to the wave period, the wave height does not have large impact on the performance of the Langlee WEC. There is a small tendency towards a decrease in performance for increasing wave heights, for the load settings 1 and 2, and the opposite reaction with higher load settings, 4 and 5. In general, we can presume that they are very close to being independent.

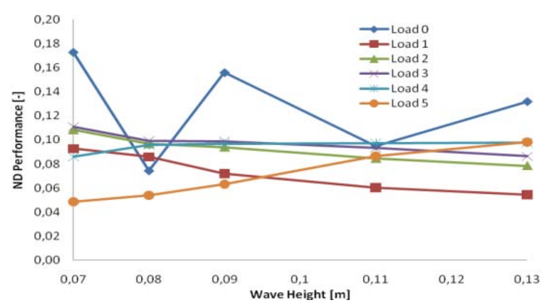

Fig.7: Evaluation of the dependency of the model towards wave height in regular waves

As the performance of the device is much more dependent on the wave period than on the wave height, the wave period will be used as the main parameter to characterize a certain wave condition, if the wave states are not applicable.

Natural Frequency of Motion

The periods of natural frequency are essentially the same for the heave, roll and pitch motion. This is expected as the main frame is squared and symmetric, except for the water wings and the PTO systems, which might cause the small differences. The model did not present any natural frequency of oscillation in surge as the model is over-damped in this direction. This is due to the perpendicular placement of the water wings towards the surge movement. The loading of the PTO system on the vertically standing water wings was set so that they could not move during the tests.

Table 4: The natural frequencies of oscillation in heave, roll and pitch

Natural frequency of	Period [s]
Heaving	2.13
rolling	2.15
pitching	2.1

Transfer Function in Regular and Irregular Waves

In the next graphs, the transfer function of the wave to the heave, surge and pitch motion of the model is given for regular and irregular waves. It was decided to neglect the spectral density values of the incident waves when they were smaller than 0.5% of the maximum spectral density value. This is the reason for the sudden drop of the transfer function of the irregular waves that can be noticed at the lowest frequencies.

The heave transfer function is very similar for regular as for irregular waves. In both cases, the peak transfer coefficient can be found around 0.47Hz which corresponds to a wave period of 2.13s, the natural frequency of oscillation. For the larger waves, having an Hs and Tp of 0.07m and 1.5s, the peak is not well defined and it has the tendency to shift to lower frequencies. However, their direct response motion (not represented here) is clearly also around the frequency of natural oscillation. The transfer coefficient curve is also relatively narrow banded, which indicates that the structure is only reacting significantly to a small range of wave periods.

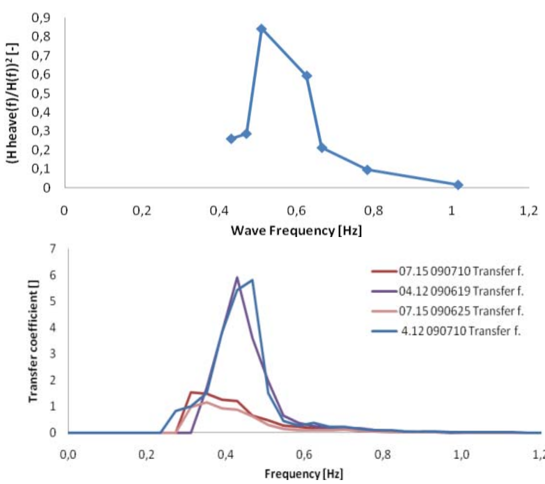

Fig.8: Heave transfer function for regular (upper) and irregular waves (lower)

There is a strong correlation between the transfer functions of the surge motion for the regular and irregular waves. The transfer function is highest at low frequencies and decreases gradually to negligible values at 0.8Hz or 1.25s, which corresponds to the peak frequency in matters of efficiency. At this wave period the water wings move in opposite directions, which cancel out the surge motion of the device. We would have expected the transfer function coefficient to increase for higher frequencies but as the model is over-damped in the surge motion, the motion at high frequencies is very limited.

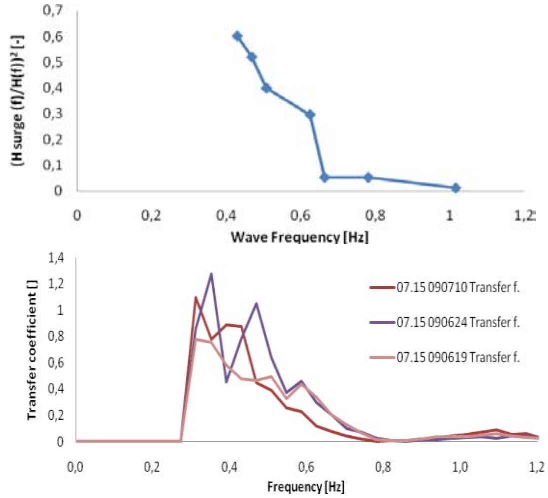

Fig.9: Surge transfer function for regular (upper) and irregular waves (lower)

The transfer functions for the pitch motion in regular and irregular waves show a very similar trend, except that the peak of the pitch transfer function has shifted to a slightly lower frequency, around 0.4Hz for the irregular waves, while it is around 0.5Hz for the regular waves. However, the peak of the response function (not represented) is still around 0.5Hz. The curve 07.15 090624 shows a lot of noise at high frequencies, but a clean trend can be distinguished. Also here, it can be observed that the transfer function is relatively narrow banded for the pitch motion.

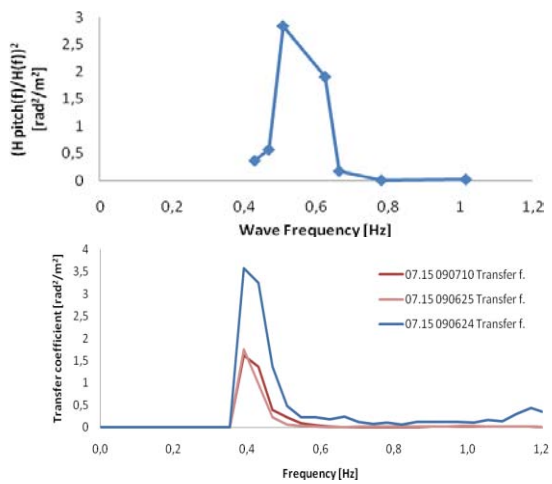

Fig.10: Pitch transfer function for regular (upper) and irregular waves (lower)

In general, the transfer functions from the wave to the heave and pitch motion, as well in regular as in irregular waves, show very consistent results. We can observe that around the wave period of peak performance, the transfer function factor in the three motions is almost negligible and that the main peak of the transfer functions is close to the natural frequency of motion. For the surge motion, the transfer function decreases while getting closer to the wave period of peak performance, as expected.

Performance Analysis

Non-dimensional Performance of the Langlee WEC

Based on the performance results of the model in the various wave states that were realized in the wave basin, a performance curve was constructed. From this curve, an approximation of the performance of the device for other wave conditions was obtained by interpolation. The next graph (Fig.11) shows that the derived performances of the model for other wave conditions, in this case the 1:20 and 1:30 scaled wave conditions of Horns Rev 1, closely follow the trend of the experimentally obtained results.

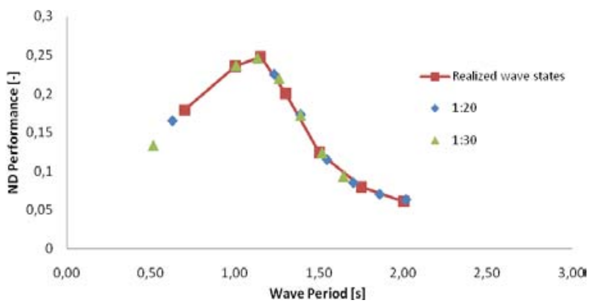

Fig.11: Representation of the obtained and estimated ND performances

Predicted Performance for Horns Rev 1

The next figure (Fig.12) summarizes the estimated performance of the Langlee WEC at Horns Rev 1 for two different scaling lengths. A scaling ratio of 1:20 corresponds to a device measuring 25 x 25m and 37.5 x 37.5m respectively at a scaling ratio of 1:30. On Fig. 11, the effect of the scaling ratio can be seen. A greater scaling ratio reduces the lab-equivalent wave conditions, and therefore shifts the non-dimensional performance points more to the left on the performance curve. This results in having more performance points close to the peak of the curve and consequently increases the performance.

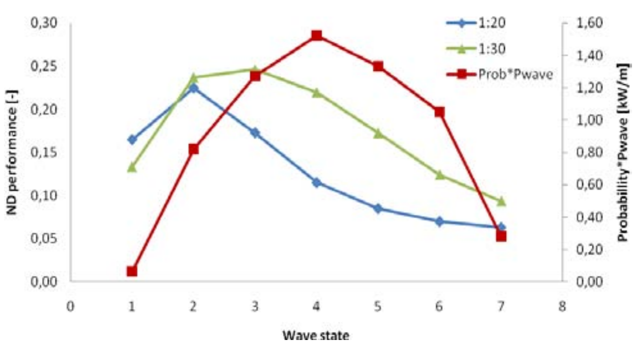

Fig.12: Estimated performance of the model for the 7 wave states characterising Horns Rev 1 and for 2 different scaling ratios

The maximum performance of the device is obtained around wave state 2 for 1:20 scale and close to wave state 3 for 1:30 scale. This shows the importance of the scaling ratio as the wave state of best performance of the device can be shifted towards the peak of the available wave power curve, shown by the red line. The 1:30 scale will therefore produce more energy, require a greater generator capacity and will therefore endure higher forces. Even a 1 to 40 scale of the model or larger could be conceivable, especially if they would enhance the survivability of the device and be economically favourable, as the installation cost per farm might be lower for fewer, larger structures.

Table 5 summarizes some of the wave state characteristics found at Horns Rev 1, and shows the power output of the Langlee for assumed 1:20 and 1:30 scaling lengths. The yearly average generating power is improved by 50 %, going from 0.79 kW/m at scale 1:20 to 1.24 kW/m for scale 1:30, corresponding to a yearly production per meter which goes from 6.97 MWh/y/m to 10.85 MWh/y/m.

Table 5: Performance estimation for two scaling ratios at Horns Rev 1

Horns Rev 1				1:20 (25m)			1:30 (37.5m)		
Wave State	Pwave	Prob	Prob* Pwave	ND Perf.	Power prod	Pgen	ND Perf.	Power prod	Pgen
	kW/m	%	kW/m	-	kW/m	kW/m	-	kW/m	kW/m
1	0.3	21.3	0.06	0.17	0.01	0.05	0.13	0.01	0.04
2	2.4	34.2	0.82	0.23	0.18	0.54	0.24	0.19	0.57
3	6.0	21.2	1.27	0.17	0.22	1.04	0.25	0.31	1.48
4	11.8	12.9	1.52	0.12	0.18	1.36	0.22	0.33	2.59
5	20.2	6.6	1.33	0.09	0.11	1.72	0.17	0.23	3.49
6	31.8	3.3	1.05	0.07	0.07	2.23	0.12	0.13	3.95
7	46.9	0.6	0.28	0.06	0.02	2.95	0.09	0.03	4.40
Overall ND Performance [-]				0.17			0.21		
Yearly average [kW/m] 6.34					0.79			1.24	
Yearly production per m WEC [MWh/y/m]					6.97			10.85	
Max. Pgen [kW/m]						2.95			4.40
Load factor [-]						0.27			0.28

Predicted Performance for the Danish North Sea

The same procedure was followed to evaluate the performance of the Langlee WEC for the Danish North Sea conditions, as for Horns Rev 1. The only exception is that the results were processed for three scaling ratios instead of two as no obvious peak in the performance can be identified for the 1:20 and 1:30 scaling lengths.

As for Horns Rev 1 (Fig. 12), it can be noticed that the peak can be moved to where the peak of the available wave power curve is (shown by the Probability*Pwave line) by appropriate scaling. The curves of scales 1:20 (25m) and 1:30 (37.5m) show no true peak on the graph, as for these scaling ratios the device would probably have a peak efficiency at smaller wave conditions than wave state 1. The trend shown in Fig. 13 suggests that for Danish North Sea conditions a Langlee WEC of a larger scale, e.g. around 1:50, could keep on increasing the overall performance.

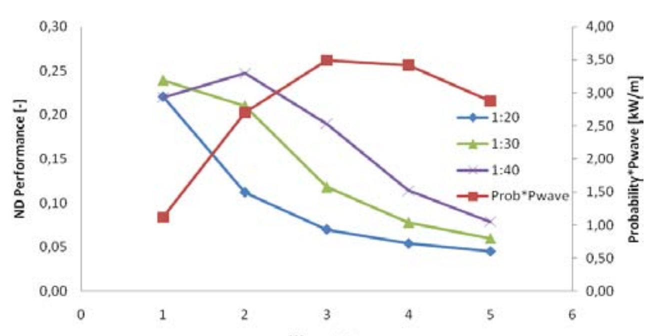

Fig.13: Performance of the model for the five wave states characterising the Danish North Sea and three scaling ratios

Table 6: Estimation of the performance of the Langlee WEC for 3 scaling ratios in Danish North Sea conditions

Danish North Sea				1:20 or 25m			1:30 or 37,5m			1:40 or 50m		
Wave State	Pwave [kW/m]	Prob [%]	Prob* Pwave [kW/m]	ND Perf. [-]	Power prod. [kW/m]	Pgen [kW/m]	ND Perf. [-]	Power prod. [kW/m]	Pgen [kW/m]	ND Perf. [-]	Power prod. [kW/m]	Pgen [kW/m]
1	2.4	46.8	1.12	0.22	0.25	0.53	0.24	0.27	0.57	0.21	0.24	0.50
2	12.0	22.6	2.71	0.11	0.30	1.34	0.21	0.55	2.45	0.25	0.66	2.93
3	32.3	10.8	3.49	0.07	0.24	2.26	0.12	0.40	3.72	0.19	0.66	6.14
4	67.0	5.1	3.42	0.05	0.17	3.35	0.08	0.27	5.36	0.12	0.41	8.04
5	119.7	2.4	2.87	0.04	0.11	4.79	0.06	0.17	7.18	0.08	0.23	9.58
Overall ND performance [-]				0.14			0.18			0.18		
Yearly average [kW/m]			13.61		1.08			1.67			2.20	
Yearly prod. pr. m WEC [MWh/y/m]					9.47			14.65			19.30	
Max. Pgen [kW/m]						4.79			7.18			9.58
Load factor [-]						0.23			0.23			0.23

Table 6 summarizes the performance and shows the power output of the Langlee for 1:20, 1:30 and 1:40 scale. The yearly average is improved to 2.20 kW/m for 1:40 scale and 1.67 kW/m for 1:30 scale from 1.08 kW/m for 1:20 scale, which is roughly 2 and 1.5 times its average generating power . This corresponds to a yearly production per meter, which goes to 19.3 and 14.7 MWh/y/m from 9.5 MWh/y/m. However, the load factor and overall efficiency stay stable around 0.23 and 0.18. This reflects that the increased difference between the average generated power to the maximum generated power stays constant and that by increasing the scale, the non-dimensional performance improves for the higher wave states but decreases for the lowest ones, where the probability of occurrence is the highest.

For the Danish North Sea conditions, it is difficult to define the appropriate scaling ratio. On one hand the yearly production still increases significantly but the overall efficiency and load factor stay constant between the 1:30 and 1:40 scale. In reality, we might want to avoid operation in the harshest conditions, e.g. to improve survivability, or choose not to operate in low yielding wave states, e.g. in order not to use unnecessarily the equipment. Besides these parameters, financial and economical issues might even be more predominant.

Effect on the Performance of Model or Setup Alterations

Fixed Structure

Fig. 14 emphasizes the potential performance that could be gained by having a fixed structure instead of one that is almost “free to move”. Although not many points have been investigated, it appears to be very beneficial to restrict the motion of the device. This can be done on various ways: by implementing added mass, by modifying the structure in order to stabilize it or by improving the mooring setup. Besides the positive impact of the modification, the best way to restrict the motion may depend on various factors such as the location of implementation, corresponding costs and survivability issues. A positive detail is that the potential improvement in performance is greater for larger waves, where the ND performance was the lowest. This could broaden the high efficiency range and consequently avoid greater or improve smaller structures.

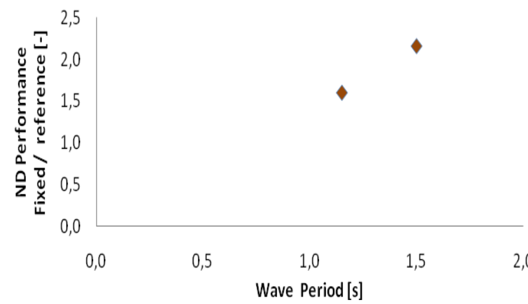

Fig.14: The effect on the performance by using a fixed structure instead of the reference slack-moored device

Damping Plates

As can be observed in the next graphs (Fig. 15), the heave motion of the device is significantly influenced by the damping plates. The relative heave motion of the device is reduced by approximately 70%, in all the tested wave conditions.

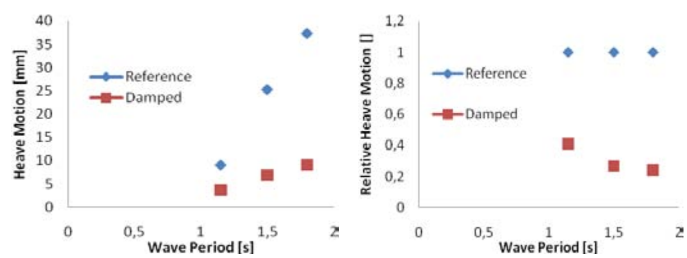

Fig. 15: The absolute ($H_{1/3}$) and relative heave motion of the device with and without damping plates

Surprisingly, the damping plates also significantly reduce the surge motion of the device, as can be visualized in Fig. 16. The test performed with the smallest wave conditions achieved a slightly higher value when the damping plates were mounted. As movements were very small during this test, some small factors, such as the reproducibility of the waves, might have excessively influenced these results.

The damping effect of the plates on the surge motion is relatively unexpected as greater surge motions would be expected, due to the damped heave motion. The relative damping of the surge motion also appears to increase with the wave conditions, from almost nothing for the smallest wave conditions, until close to 60% for the greatest.

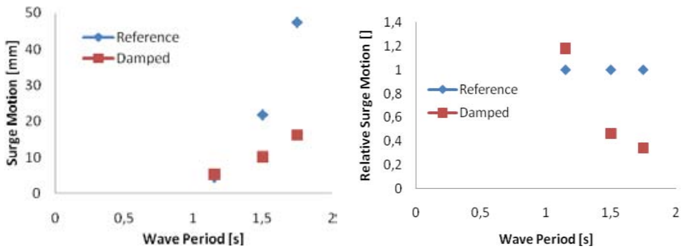

Fig.16: The absolute ($H_{1/3}$) and relative surge motion of the device with and without damping plates

Similarly to the surge motion, the influence of the damping plates on the pitch motion appears to increase with the wave conditions. At the small wave conditions they have small impact while for greater wave conditions they can achieve up to 80% reduction in pitch motion.

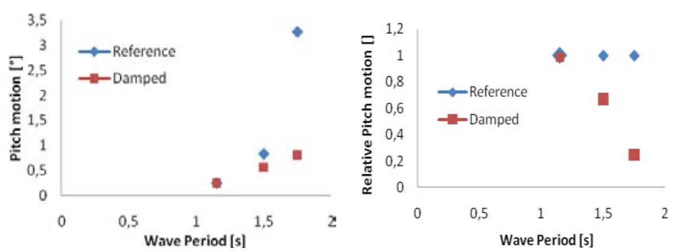

Fig.17: The absolute ($H_{1/3}$) and relative pitch motion of the device with and without damping plates

Although the plates were helpful in damping the motion of the device, they apparently only slightly increase the efficiency of the device. This is rather surprising as the plates stabilised the device significantly, especially for larger wave periods. However, the damping plates only reduce and do not prevent the motion, so the damping plates alone might not be sufficient to harvest a significant part of this "potential additional performance".

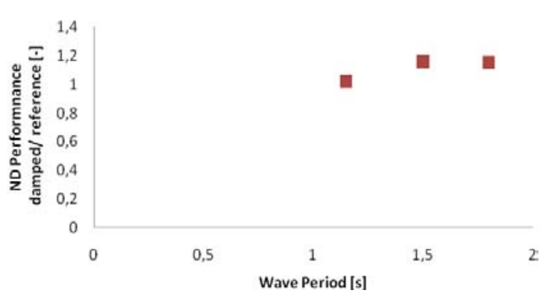

Fig.18: The relative influence of the damping plates on the performance of the Langlee WEC for 3 different irregular wave conditions

Oblique Waves

The results in Fig. 19 show that there is a larger loss of efficiency when the water wings actively taking readings are on the far side of the device, as only the two water wings of the left side were equipped with force transducers. In this setup they are partially blocked from the waves by the two water wings without force transducers. On the other hand, when the waves are coming from the opposite side, so no blocking occurs, the efficiency on the water wings with measured performance drops significantly less. An overall loss in performance of approximately 40% was found for incoming waves with an angle of attack of 45°.

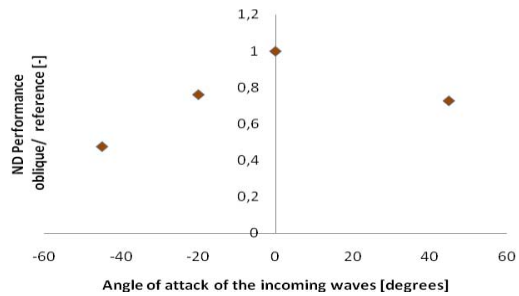

Fig.19: The effect of directional waves on the performance of the Langlee WEC for irregular waves of 0.05m and 1.5s

In conclusion, the angle of attack of the incoming waves has a significant effect on the efficiency of the device but does not prevent the device of working even at angles of attack of 45°. This effect could be diminished by the spreading of the waves or avoided by having a directional mooring system, depending on the directional spreading of the waves at the specific location.

Waves with Directional Spreading (3D waves)

Fig. 20 shows that as the waves become more 3D than 2D the efficiency drops slightly. The performance tends to decrease slower for irregular waves, which have their main period closer to the wave period of peak performance than others. For the evaluated locations, Horns Rev 1 and the Danish North Sea, the directional spreading is expected to correspond to a spreading factor, S, of 10 (value 1 on the graph). Many structural parameters could have an influence on the effect of the directional spreading, e.g. the shape of the water wings, so this reduction in efficiency could be limited.

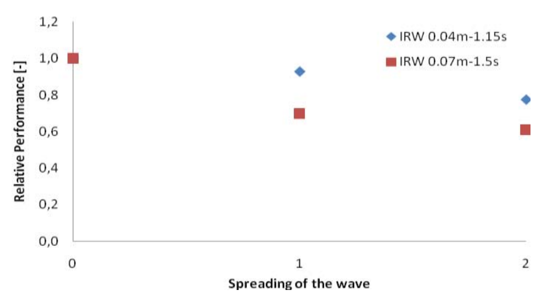

Fig.20: The effect of 3D waves on the performance of the Langlee WEC. Spreading value 0 corresponds to 2D waves and 2 to full 3D

CONCLUSIONS

This study can be considered as a proof of concept, as the Langlee device is able to convert power from the waves into useful mechanical power, which can then, through further mechanical and electrical systems, be converted into electricity.

The overall power production capabilities of the Langlee device has been estimated for two locations of interest and an investigation on various structural and conditional changes has been carried out. The estimated yearly-average non-dimensional performance for different scaling ratios Horns Rev 1 and the Danish North Sea ranges from 0.14 to 0.21, and the estimated yearly power production is from 6.97 to 19.30 MWh/y/m, depending on the location and scale.

Table 7: Summary of the main estimated performance characteristics of the Langlee WEC at Horns Rev 1 and for Danish North Sea

	Horns Rev 1		Danish North Sea		
	1:20	1:30	1:20	1:30	1:40
Yearly average Power [kW/m]	0.79	1.24	1.08	1.67	2.20
Overall ND Performance [-]	0.17	0.21	0.14	0.18	0.18
Yearly prod. per m [MWh/y/m]	6.97	10.85	9.47	14.65	19.30

Various behavioural characteristics were emphasized during this study. Some of the most important are:

- The performance of the device is very dependent on the wave period, but hardly on the wave height.
- The peak in performance is well-pronounced when the wavelength measures twice the length of the model. The performance tends to decrease more severely for higher than for lower wave periods.
- The frequency of natural oscillation can clearly be recognized in the transfer function for heaving and pitching, as well in regular as in irregular waves.
- The Langlee model achieved significantly higher performances, 60-115%, when its structure was fixed. But, although the damping plates considerably attenuated the heave, surge and pitch motion of the device, they only improved the performance by 20% in the larger wave states. Other alterations, such as an adapted mooring setup might make a significant difference. However, these options have not been included in this study.
- Oblique waves reduced the performance by approximately 25% for an angle of attack of 20° and by approximately 40% for an angle of 45°.
- The effect of directional spreading of the wave was limited as a 10-30% performance drop is expected at the investigated locations.

This first experimental study on the Langlee WEC model has given promising outcomes as the performance results are good and various potential ways have been encountered that could further enhance it.

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