Wave Energy, Lever Operated Pivoting Float LOPF Study

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by

Lucia Margheritini

December 2011

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EXECUTIVE SUMMARY

The fully instrumented Resen Waves Lever Operated Pivoting Float LOPF wave energy buoy model has gone through the first stage of testing in regular waves in scale 1:25 of the North Sea wave conditions, in the 3D deep wave basin at the Hydraulic and Coastal Engineering Laboratory of Aalborg University in Denmark.

The model size was 60cm W x 90cm L x 21cm H. The 60 cm width pointed towards the wave front. The LOPF buoy is characterized by a simple mechanical design with few moving parts and direct electrical output and it is taut moored to the sea bed, so all forces are referenced to the seabed for maximum energy output in regular as well as irregular waves. During storms the buoy pivots and streamlines itself to minimize loads on the mooring line.

A conservative estimate shows that a full scale system for North Sea conditions has a float size width of 15 m that will, with 60% generator efficiency, produce 723 MWh/y (723.000 kWh/y) with an average power output of 82,5 kW, which requires a generator capacity of 250 to 300 kW. It is expected the generator efficiency can be increased to 90% in the future. In addition there are several areas for future improvements for increased power production.

Technical description: The buoy consisted of two parallel floats, which were locked together and a cylindrical pivoting arm, between the two floats. The arm is allowed to rotate independently of the floats. When the waves pass the buoy the rotation of the arm relative to the floats generates electricity with a generator inside the float. Direct measurements on the device comprised of the voltage output of the generator, the amperes produced by the generator, the torque on the generator itself, the arm bending moment produced by the mooring line from which also the mooring forces are derived and the relative angle between the arm and the float, respectively. All the data was managed by the CMC-99 data logger at 10 Hz. Wave measurements were separately acquired and managed by the in house built software WaveLab3 at Aalborg University. Results are presented in terms of average Mechanical and Electric Power, average and maximum mooring forces, average angular velocities and Mechanical and Electrical Efficiency. Finally the power production results are presented in full scale for the typical North Sea wave conditions with an average power level of 16 kW/m wave front (Rugbjerg & Nielsen, 1999). Results are to be considered conservative as the average efficiencies have been taken for each wave condition. It should also be considered that tests in regular waves usually show lower results in terms of power production, than in irregular wave tests, due to the lower power stored in the incoming waves, for the same sea state.

Maximum Mechanical Efficiency is 30% while Average Mechanic efficiency over the test is 16.2%. The maximum average calculated Mechanical Power is 13.3 W. Tests featuring a longer distance between the mooring point on the arm and the pivoting point show the best performance.

Electric Power measurements displayed a maximum average power of 2.3 W but it was concluded that the DC generator used was unsuitable for this application because it worked far away from the optimal RPMs and it should instead be possible to find a more suitable permanent magnet AC generator with high efficiency, usually around 90%.

Areas for improvements have been investigated both for the measuring systems and for the buoy power take off. The necessity of monitoring separately all movements of the floats and of the arm has been identified and will be implemented in the next model. This will allow a better understanding of the losses and the hydrodynamics of the system and be a valuable tool for verifying the losses and optimizing the power output. It was never the less clear that improved power capture is possible when operating with a longer distance between the mooring point and the pivoting point of the arm with the generator and it is possible to modify the system to harvest that power.

It is estimate that in full scale a 15 m buoy will be able to generate an average of 82.5 kW i.e. 723 MWh/y, if a suitable generator is used. This is based on 60% generator efficiency, but improved efficiencies of up to 90% are most likely to be met in the future. This assumes that improvements on the transmission of the power stored in the arm are made,

so all the available mechanical power is lead to the generator. If these improvements are not taken into consideration, the results at the present state of the art show an average power production of 25.3 kW i.e. 222 MWh/y.

Finally the maximum mooring forces on the 1:25 scale buoy is calculated to be 504.2 N, which is derived my measuring the moment (torque) of the arm. In general maximum forces are twice the average forces. The maximum mooring force on a full scale 15 m buoy is 25^3 x 504 N = 7.875 kN. The high mooring forces are the key to high power production.

OBJECTIVES

The objectives of the present work are:

1. To test the scale model of an innovative wave energy device, fully instrumented and equipped with power take-off, under the influence of different wave conditions.
2. To measure the power production of the device in terms of Mechanical and Electrical Power.
3. To calculate the mooring forces.
4. To investigate areas for improvements and possible losses in the conversion power line.

SETUP FOR WAVE TANK MEASUREMENTS

THE MODEL

The fully instrumented Resen Waves wave energy buoy model has been tested in the deep (0,68 m) 3D wave basin at the Hydraulic and Coastal Engineering Laboratory of Aalborg University in Denmark. It consisted of two parallel floats of (300 W x900 L x 210 H mm) and a cylindrical (900 mm long x Ø=270 mm) pivoting arm. All the measuring equipment, as well as the power take-off, is located inside the water proof arm (Fig. 1, left). The arm is allowed to rotate independently of the floats when the waves pass the buoy and the rotation of the arm generates electricity with a generator.

The wave tank is a reinforced concrete tank with the dimensions of 15.7 L x 8.5 W x 1.5 L m. The paddle system is a snake-front piston type with a total of ten actuators, enabling generation of short-crested waves. The wave generation software used for controlling the paddle system is AWASYS6, developed by the laboratory at Aalborg University.

The model was taut moored by means of a rope to the concrete bottom of the tank. The mooring line was fixed at two points of the tank bottom and tethered to a point above the water to provide a taut mooring line, leaving only the elasticity of the system itself (Fig. 1, right). During the tests the mooring position on the main arm was changed in order to investigate the influence of this parameter on the performance. The two mooring positions were offset 150 mm and 280 mm, respectively from the shaft center of the arm.

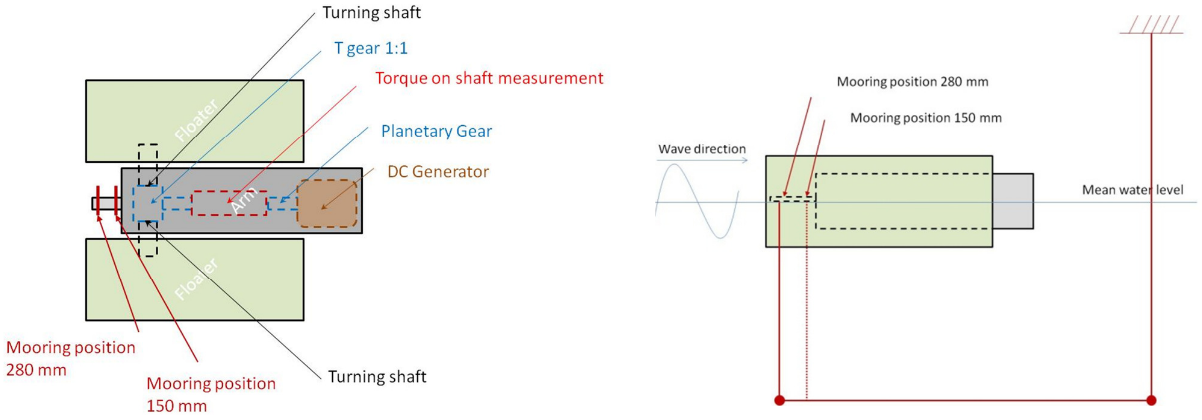


Figure 1. Definition sketch for the energy buoy model and tank testing set-up. Top view (left side) and side view with waves coming from the left (right side).

MEASURING EQUIPMENT AND DATA ACQUISITION SYSTEM

All the data have been acquired at 10 Hz.

- The waves have been measured by mean of 3 wave gauges in front of the model and the data was acquired by Wavelab3 that was used also for the wave data analysis. WaveLab3 has been developed by Aalborg University.

The fully instrumented device provided 5 different measurements after signal calibration, which were acquired by 5 parallel channels:

- Channel 1: Voltage output of the generator across an external resistor load (varying between 1 and 6 ohms, during the different tests).
- Channel 2: Voltage drop over a constant resistor of nominal 1 ohm in series with the external resistor load, which can be recalculated to the amperes produced by the generator by dividing the voltage drop by 0,93 ohms, that is the constant resistor of nominal 1 ohm.
- Channel 3: Torque directly on the generator shaft with planetary gear.
- Channel 4: Arm bending moment produced by the mooring line on the arm.
- Channel 5: Relative angle between the arm and the float.

The data from the device was acquired by mean of the CMC-99 data logger at 10 Hz.

CALIBRATION OF THE SYSTEM

The signals have been calibrated in the laboratory in a controlled environment, resulting in the calibration functions derived from Fig.2-5 for channels 1and 2, and 3, 4 and 5 respectively. In all cases, the linear regressions were close to 1 or =1 for R^2.

The Voltage from Channels 2 was recalculated to the amperes produced by the generator, by dividing it by 0,93 ohms (nominal resistance 1 ohm).

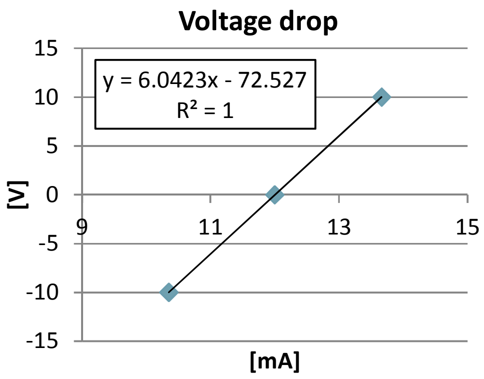


Figure 2. Calibration function from channels 1 and 2.

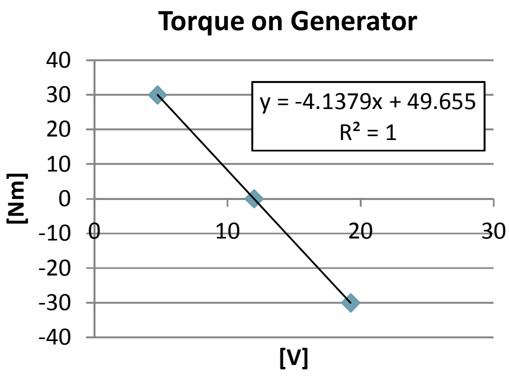


Figure 3. Calibration function for channel 3.

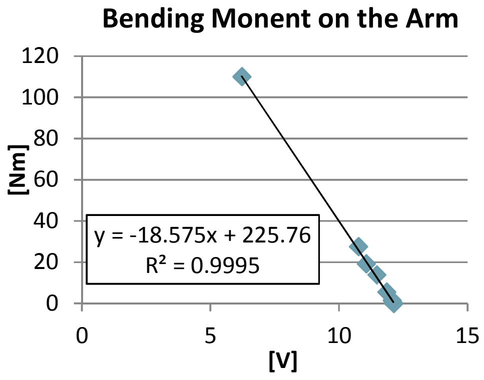


Figure 4. Calibration function for channel 4.

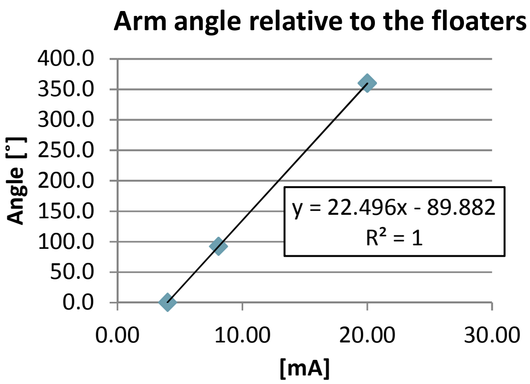


Figure 5. Calibration function on channel 5.

LABORATORY TESTS RESULTS

The wave energy device was systematically tested in regular waves and in a few irregular wave conditions, with the mooring line attached at respectively 280 mm and 150 mm from the center of the pivoting shaft. Five different resistive loads were applied to the generator: 1, 2, 3, 4 and 6 Ohms, respectively, Table 1. Tests in regular waves lasted one minute while irregular wave tests lasted 25 minutes. The name of the file contains all the information characterizing the tests:

RW/IW=regular waves/irregular waves

H6=wave condition number 6 (refer to Table 2)

T1=first wave period tested (refer to Table 2)

R=applied load, i. e. resistance in Ohms

A=mooring position

N=test counter

Target waves are derived from the North Sea conditions with slightly different wave periods (Table 2). Regular waves corresponding to irregular waves with the same energy content have been used i.e. imposing spectral moment m0 for regular and irregular waves to be the same. This means H^2regular/8=H^2m0/16, which results in Hregular=Hmo/2^0.5. The scale of the tests resulted to be around 1:25.

The wave power (Pwave) is calculated with the equation:

$$P_{wave} = \frac{\rho g^2 H^2 T}{\beta \pi} \quad [\text{W/m}]$$

Where:
ρ = water density = 1000 [kg/m^3];
g =acceleration of gravity = 9.82 [m/s^2];
H is the measured wave height provided by WaveLab (average wave height Hm) [m];
T is the measured wave period provided by WaveLab (average wave period Tm) [s];
β= coefficient =32 for regular waves.

The power in the incoming waves has then been multiplied by 600 mm (= 2 x 300mm, float widths) considered to be the average width of the device, obtaining the incoming power relative to the device width.

The Mechanic power is calculated as:

$$Mech.Power = M_{Gen} \cdot [\frac{rad}{s}] \quad [\text{W}]$$

Where the *rad/s* is converted from the angular speed [rpm] obtained from the difference between two consecutive angle measurements.

The Electrical power is directly measured out of the DC generator [W], as Voltage and Current through the external load resistor on the generator.

The average Mechanical Power and Electrical power are then calculated over a suitable set of data relative to each test.

Finally, the average mooring force for each test is calculated by dividing the average bending moment from Channel 4 [Nm] by the corresponding arm length *b* [m]:

$$F_{mean} = \frac{M_{arm}}{b} \qquad [\text{N}]$$

Table 1. Tested wave conditions and partial results. Regular waves.

File name	Hm [m]	Tm [s]	Pwave[W/m]	Pwave[W]	Av. ElP. [W]	Av. MechP1 [W]	Av. MechP2 [W]
RW_H6T1R6A150N1	0.173	2.800	80.716	48.430	2.325	14.878	13.234
RW_H6T1R3A150N1	0.163	2.801	71.683	43.010	2.236	13.130	11.900
RW_H6T1R2A150N1	0.164	2.809	72.375	43.425	1.723	12.347	10.525
RW_H6T1R1A150N1	0.169	2.810	76.820	46.092	1.186	11.557	11.147
RW_H5T1R6A150N1	0.149	2.515	53.707	32.224	0.474	9.431	5.128
RW_H5T1R3A150N1	0.149	2.510	53.330	31.998	0.458	8.701	4.726
RW_H5T1R2A150N1	0.148	2.525	52.866	31.719	0.401	8.293	4.191
RW_H5T1R1A150N1	0.148	2.523	52.729	31.638	0.285	7.745	3.628
RW_H4T1R6A150N1	0.120	2.240	30.718	18.431	0.383	9.679	4.443
RW_H4T1R3A150N1	0.121	2.249	31.465	18.879	0.436	8.994	4.622
RW_H4T1R2A150N1	0.119	2.250	30.699	18.419	0.392	8.868	4.267
RW_H4T1R1A150N1	0.115	2.243	28.690	17.214	0.233	8.042	4.096
RW_H3T1R6A150N1	0.121	1.962	27.565	16.539	0.219	8.872	3.349
RW_H3T1R3A150N1	0.119	1.963	26.768	16.061	0.234	8.112	3.133
RW_H3T1R2A150N1	0.121	1.963	27.746	16.648	0.203	7.844	3.212
RW_H3T1R1A150N1	0.118	1.964	26.268	15.761	0.108	7.039	2.657
RW_H2T1R6A150N1	0.096	1.683	14.733	8.840	0.012	4.905	0.675
RW_H2T1R3A150N1	0.094	1.680	14.350	8.610	0.020	4.959	0.676
RW_H2T1R2A150N1	0.090	1.682	13.166	7.899	0.010	4.871	0.673
RW_H2T1R1A150N1	0.093	1.678	13.998	8.399	0.012	4.753	0.667
RW_H1T1R6A150N1	0.066	1.403	5.860	3.516	0.003	1.898	0.200
RW_H1T1R3A150N1	0.063	1.403	5.416	3.250	0.004	1.871	0.202
RW_H1T1R2A150N1	0.065	1.406	5.667	3.400	0.004	1.559	0.172
RW_H1T1R1A150N1	0.064	1.403	5.591	3.354	0.004	1.912	0.210
RW_H6T2R4L280N1	0.174	2.812	81.497	48.898	1.946	38.519	12.686
RW_H6T1R4L280N1	0.165	2.809	73.772	44.263	2.120	41.511	13.273
RW_H6T1R3L280N1	0.171	2.808	78.854	47.313	1.863	38.635	12.706
RW_H6T1R2L280N1	0.177	2.810	84.923	50.954	1.482	35.297	11.356
RW_H5T2R4L280N1	0.140	2.258	42.555	25.533	0.478	29.320	5.556
RW_H5T1R4L280N1	0.140	2.522	47.481	28.489	0.369	24.814	4.339
RW_H5T1R3L280N1	0.140	2.520	47.426	28.455	0.323	23.875	4.124
RW_H5T1R2L280N1	0.140	2.522	47.517	28.510	0.268	22.832	3.915
RW_H4T2R4L280N1	0.136	2.102	37.185	22.311	0.088	20.114	2.341
RW_H4T1R4L280N1	0.127	2.248	34.850	20.910	0.189	22.635	2.928
RW_H4T1R3L280N1	0.128	2.237	35.322	21.193	0.191	22.544	2.914
RW_H4T1R2L280N1	0.129	2.244	35.625	21.375	0.166	21.904	3.048
RW_H3T2R4L280N1	0.121	1.702	23.974	14.384	0.021	16.523	1.224
RW_H3T1R2L280N1	0.113	1.923	23.523	14.114	0.036	17.650	1.820
RW_H2T2R4L280N1	0.110	1.485	17.380	10.428	0.006	12.779	0.776
RW_H2T1R2L280N1	0.088	1.686	12.408	7.445	0.005	11.520	0.770

Table 2. Target Wave Conditions, full scale.

Number	H [m]	Hs [m]	T1 [s]	T2[s]
-	-	-	-	-
1	1.4	2.0	5.7	-
2	2.1	3.0	6.8	6.1
3	2.8	4.0	7.9	6.9
4	3.5	5.0	9.0	8.5
5	4.3	6.0	10.2	9.3
6	5.0	7	11.3	10.5

THE CONVERSION OF POWER IN THE POWER TRAIN FROM MECHANIC TO ELECTRIC POWER

The conversion of power in the power train is considered as follow:

Wave power ⟶ Mech. Power ⟶ Electrical Power, identifying two different stages.

Starting inside the device, we can see that big losses occur in the conversion of the Mechanical power to the Electric power (last stage of the conversion) (Fig.6). These losses are bigger for bigger wave heights and are in the range of 0.6-18.8 %, with the highest lost occurring in the tests RW_H6T1R3A150N1 with H=0.164 m, T=2.801, corresponding to a loss of around 9.7 W. This may be due to the DC generator running far away from its optimal speed and thus the load from the generator being too low. Maximum angular velocities recorded are around 19-17 rpm for wave conditions H6 and mooring position 150 mm.

The higher Mechanical efficiency calculated is 30% and corresponds to the test RW_H6T1R4L280N. In general the higher Mechanical efficiencies occur for wave condition H6 and the lower results are for wave condition H1 (the minimum Mechanical efficiency was calculated as 5.1% , which corresponds to the tests RW_H1T1R2A150N1).

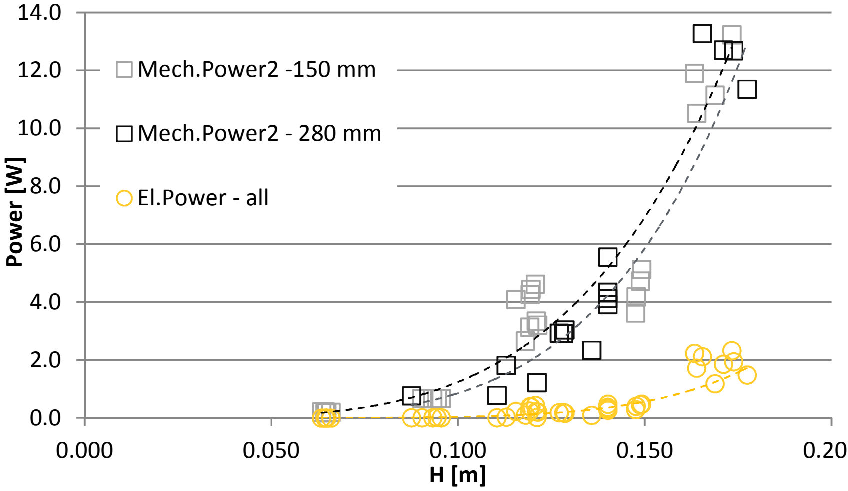


Figure 6. Comparison between Mechanical power and Electric power outputs depending on the measured wave high, from all the tested conditions in regular waves.

Considering the hydrodynamic/hydraulic performance of the device, i.e. the first stage of the power conversion from Wave power to Mechanical power, it was evident from visual observations (Fig. 7) that the device was not optimized in its shape and therefore was not moving optimally under the wave action: A lot of splashing and forth and back movements indicated significant losses. Streamlining the device and the floats, as well as realizing a more rigid mooring configuration, will help in improving the overall performance.

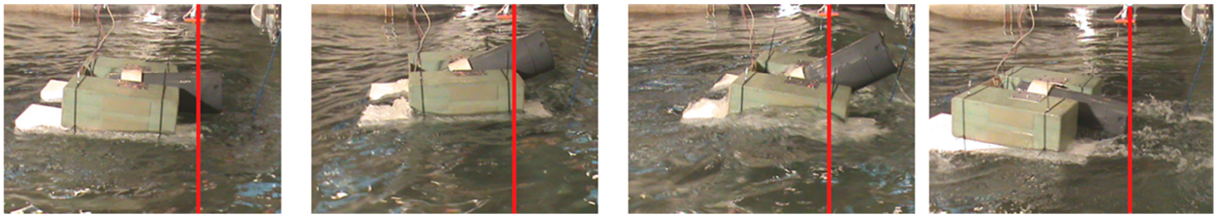


Figure 7. Typical movements of the energy buoy under regular wave tests. One wave cycle.

The load was applied directly on the generator as a resistance that was varied during the tests, from 1 to 6 Ohms, 1 Ohm providing the highest load (Fig 8 and 9). Higher Electrical efficiency corresponds to wave condition H6 (in line with the highest Mechanical efficiency) and the higher rpm, and varies between 5.2% and 0.1%. No significant differences can be seen for the different wave conditions with respect to the optimal load. It is indeed possible to notice, despite the lack of few “data points” that all the efficiency curves peeks between 3 and 6 Ohms. As expected, the angular velocity ω [rad/s] is decreasing, when the electric load is increased.

Angular speed varies between 0.57 [rad/s] for test RW_H6T1R4L280N1 and 0.07 [rad/s] for RW_H1T1R2A150N1. Higher angular speeds correspond to bigger waves with little difference between the two mooring configurations. This last statement that describe no significant difference for the “150 mm” and the “280 mm” configuration goes against the physical observation during the tests, where the main arm seemed to move faster for the short 150 mm arm. This could be explained by the fact that the angular velocity is derived by the difference between two consecutive angular measurements (Channel 5), where the measured angles are the relative angles between the floater and the arm. If the arm and the floater do not move completely independently, then the visual observation can lead into error. The same trend, depending on the wave height, can be noticed for the torque on the generator.

Finally, as expected, the torque on the generator is bigger for bigger angular speeds (Fig. 10).

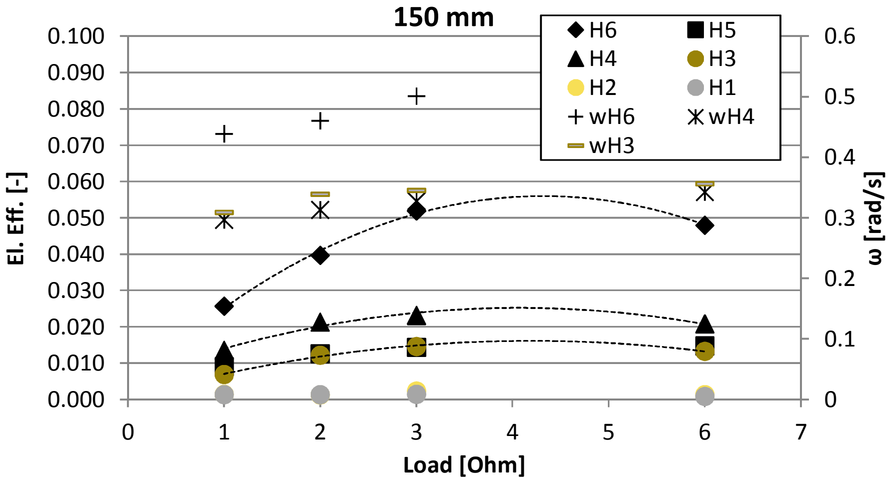


Figure 8. Electric Efficiency depending on different loads, for different wave conditions. Secondary y axis displays the angular velocity for different loads for 3 selected wave conditions. 150 mm mooring configuration.

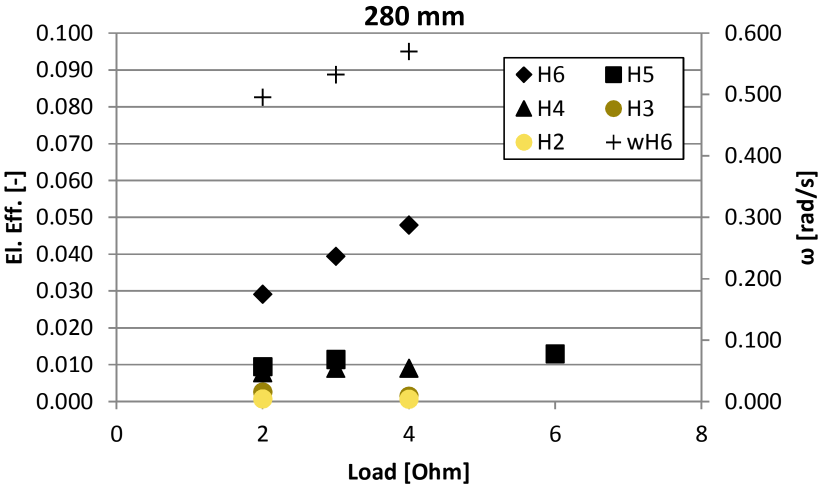


Figure 9. Electric Efficiency depending on different loads, for different wave conditions. Secondary y axis displays the angular velocity for different loads for wave condition H6. 280 mm mooring configuration.

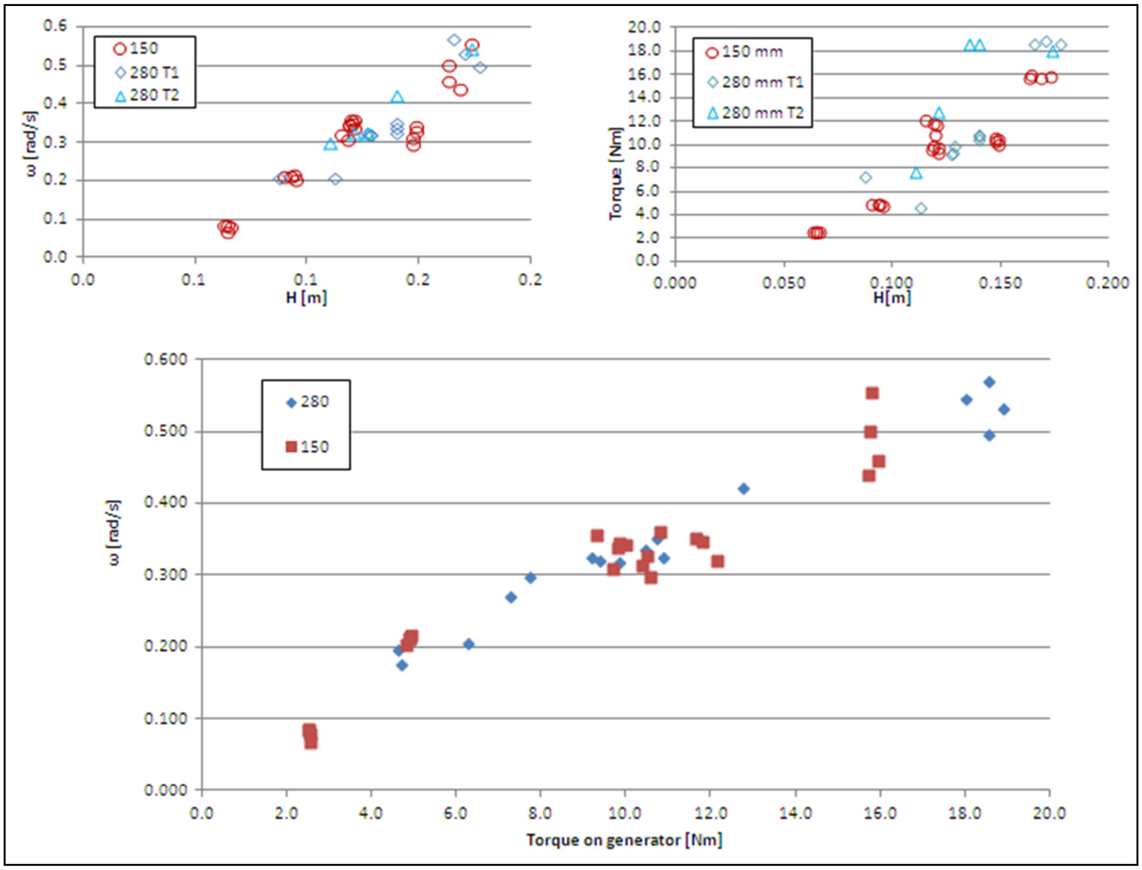


Figure 10. Top left: angular speed depending on measured wave height, for the different tested configurations. Top right: torque on generator depending on measured wave height, for the different tested configurations. Central bottom: Angular velocity depending on the torque on the generator.

MOORING FORCES

Mooring forces are here presented as average forces derived from the average bending moment on the arm during the individual tests (Fig. 11).

Higher forces occur for the mooring configuration “280 mm”, which represents the a longer arm. The biggest calculated force over the tests is 265.71 N, corresponding to the test RW_H6T1R4L280N1, while the smallest for the same configuration is 232.40 N, for RW_H2T1R2L280N1, which is in smaller waves. The average mooring force over the tests with “280 mm” configuration was 250.0 N.

For the configuration “150 mm”, the biggest mooring force is 175.01 N for RW_H6T1R6A150N1, while the smallest is 149.16 N for RW_H1T1R1A150N1. The average mooring force during the tests with “150 mm” configuration is 161.9 N.

In general bigger mooring forces correspond to bigger waves as expected. The difference between the two averages of the mean forces characterizing the two configurations is 87.9 N.

When we looked at the maximum recorded bending moment during the tests and deriving from it the mooring forces (Fig. 12), we obtain a maximum mooring force of 341.9 N for the “150 mm” configuration and 504.2 N for the “280 mm” configuration, respectively. Both values were twice as big as the biggest average recorded forces. In addition, there is a clear trend, that the forces increase with the wave height, as expected.

The difference between the two averages maximum forces, characterizing the two configurations, respectively “150 mm” and “280 mm”, is 131.3 N.

These calculations are to be considered correct in the order of magnitude, but the direct mooring forces and statistical analysis of the data in irregular waves should be carried out on previous design. In this particular case it is possible to measure only the vertical component of the mooring force. This represents, in all cases at least 87% of the total forces, if we consider an inclination of the mooring line of 30˚ from the vertical position, to stay on the conservative side.

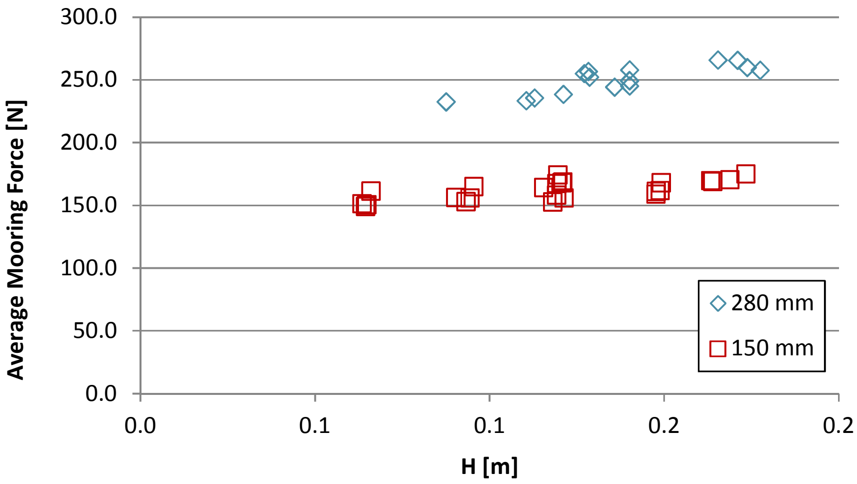


Figure 11. Average mooring force depending on the wave height for the two different configurations.

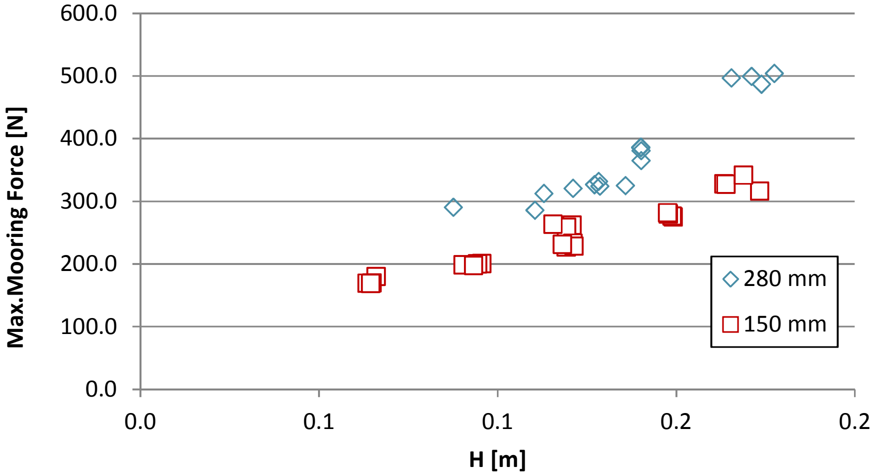


Figure 12. Maximum mooring force recoded over the tests depending on the wave height, for the two different configurations.

CRITICAL FACTORS AND FUTURE AREAS FOR IMPROVEMENTS AND FURTHER INVESTIGATION

It would be beneficial to be able to harvest all the energy that is captured in the arm (bending moment) with the 280 mm configuration. The Mechanical Power in the arm is calculated as:

$$Mech.Parm = M_{arm} \cdot [\frac{rad}{s}]$$

It is obvious that there is significant difference between the Mechanic power in the arm and the Mechanical Power calculated in the previous chapters derived from the torque on the generator (Fig 13 and 14). The losses (or the missed power capture) are present in all tests and are bigger for the 280 mm configuration (Fig.15). The average losses between Mechanical Power in the arm and Mechanical Power for all the tests are 32.5%.

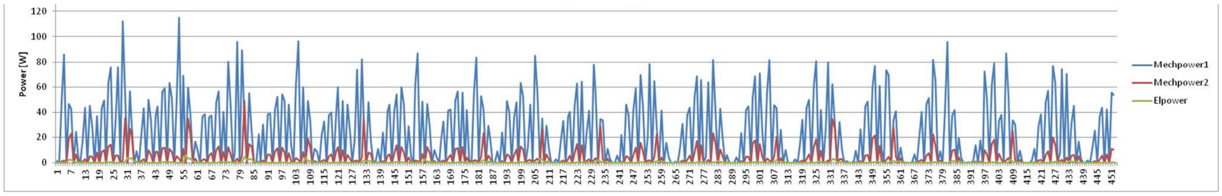


Figure 13. Comparison of Mechanic Parm (blue), Mechanic Power (red) and Electric power (green) generated during the test H5T1R4L280N1 in regular waves.

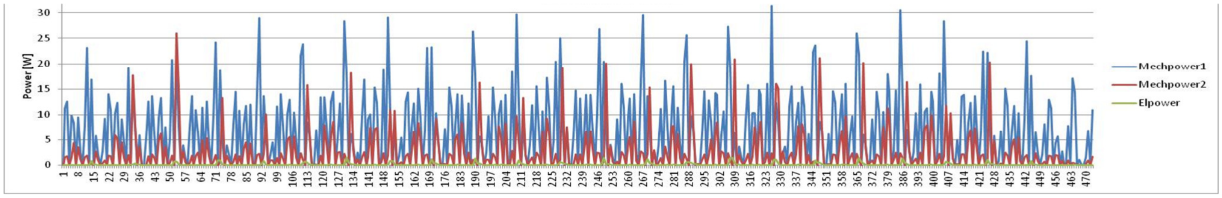


Figure 14. Comparison of Mechanic Parm (blue), Mechanic Power (red) and Electric power (green) generated during the test H3T1R1L150N1 in regular waves.

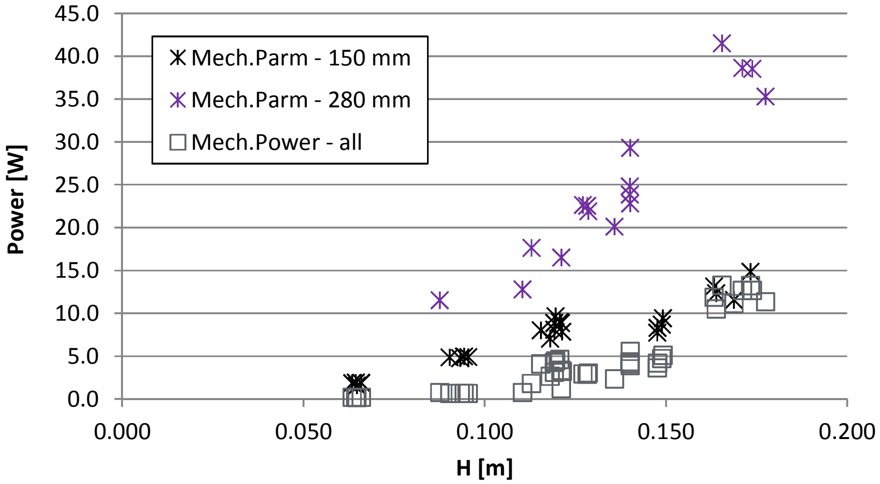


Figure 15. Difference between Mechanical power calculated from the bending moment in the arm and the Mechanical power calculated with the torque on the generator, for different wave conditions.

Power capture can be improved in all the conversion steps providing an improvement to the already good performance of the device.

In order to better monitor the device movements it is essential to have two separate masurements for the movements of the float (pitch in relation to back – front direction) and the relative angle between the floater and the arm, respectively. This would allow a deeper study on the forces acting on the float and on the arm and their correlation. The lack of this condition has been identified as a disadvantage in the present measuring system, but can be improved by using a 3-axis attitude sensor on the float itself. The main challenge is how to transmit all the Mechanic Power from the arm to the next stage of conversion. This has to be investigated further.

In addition, the load on the generator varies a lot, depending on the rpm, that is also critical information. With respect to the Electrical Power, the choice of a more suitable generator working in the proper range of rpm should increase the generator efficiencies above 60%, without any problems.

Finally, the test set up would benefit from deeper water, because it improves the quality of the generated waves. Problems in the wave generation are summarized in the Appendix.

SCALING OF THE SYSTEM AND EXPECTED POWER PRODUCTION

The wave conditions generated in the laboratory have been related to the corresponding irregular wave conditions in full scale and the wave power has been calculated with the equation:

$$P_{wave} = \frac{\rho g^2 H_S^2 T_p}{\beta \pi} \quad [\mathrm{W/m}]$$

Where:
ρ = water density = 1020 [kg/m3];
g =gravity acceleration = 9.82 [m/s2];
Hs is the significant wave height [m];
Tp is the peak period [s];
β= coefficient =64 for irregular waves.

The result was multiplied by 15.6 m (which corresponds to the width of 0.60 m times 25, the scaling factor), which has been decided to be the scale model length for the tests, in order to obtain the available power in kW.

The device performances are summarized in Table 3, in full scale. In order to fill out the table, some assumptions had to be made which are explained below.

First, the Electric efficiency has been regarded as too low and inaccurate to make any conclusions. Consequently the Mechanic Efficiency of the arm has instead been used as the point of departure and has been taken as the average for each wave condition over all the tests, assuming that the power capture will be improve so it is possible to exploit this potential.

The available power was first multiplied by the Mechanical efficiency of the arm to obtain the corresponding Mechanical Parm in irregular waves (for Hs=1 there were no available data, so an assumption of 60% efficiency was taken) and then from the resulting power, a loss of 32.5% were applied to take into account losses between the Mechanic Parm and Mechanical Power (corresponding to the average losses between MechParm and MechP over all the tests) and then 40% losses were applied, assuming that it will be possible to find a generator with 60% efficiency. PM Generators can improve the generator efficiency to typically 80% to 90%, therefore it is believed the analysis is on the conservative side.

By the results of the tests and the analysis of the data, it is expected that a 15 m buoy will be able to generate an average of 82.5 kW i.e. 723 MWh/y, if a suitable generator is used. This is based on 60% generator efficiency.

Table 3. Expected power production, full scale.

Hs [m]	Tp [s]	Pwave [kW]	Prob [%]	Available [KW]	Device MechParm Eff [%]	Mech Parm [KW]	Applied 30% loss to MechP [kW]	Applied 40% loss to Generator [kW]	Generated power [kW]
1.0	4.6	35.1	46.8	16.4	60.0	21.1	14.8	8.9	4.1
2.0	5.7	175.3	22.6	39.6	81.9	143.6	100.5	60.3	13.6
3.0	6.8	467.7	10.8	50.5	78.5	367.4	257.2	154.3	16.7
4.0	7.9	964.4	5.1	49.2	57.8	557.9	390.5	234.3	11.9
5.0	9.0	1716.0	2.3	39.5	75.3	1291.9	904.3	542.6	12.5
6.0	10.2	2806.3	2	56.1	59.1	1659.3	1161.5	696.9	13.9
7.0	11.3	4229.9	1	42.3	54.8	2317.2	1622.0	973.2	9.7
			TOT KW available	**293.6**				**TOT KW produced**	**82.5**

Without the assumption that the Mechanical Power in the arm (MechParm) can be adequately harvested and use, it is expected that a 15 m buoy will be able to generate an average of 25.3 kW i.e. 222 MWh/y, and a suitable generator is used. This is based on 60% generator efficiency and considering the improvement in the Mechanical Power can be achieved.

CONCLUSIONS

1. The fully instrumented wave energy buoy model has been tested in 6 different wave conditions in scale 1:25 to the North Sea condition. Five different loads have been applied for two distinct mooring configurations: “150 mm” and “280 mm”, indicating the distance of the mooring point to the center of the shaft, and relative efficiencies calculated. Maximum Mechanical Efficiency is 30% corresponding to H=0.17 m, T=2.81 s and load = 4 Ohm, for mooring configuration “280 mm”. In general this configuration features the best efficiencies over the tested conditions. The average Mechanical efficiency over the tests is 16.2%
2. The power production of the device has been measured in terms of Mechanical and Electrical Power. The maximum average Mechanical Power is 13.3 W, also corresponding to H=0.17 m, T=2.81 s and load = 4 Ohm, for mooring configuration “280 mm”. Electric Power measurements displayed a maximum average power of 2.3 W but it was concluded that the DC generator used was unsuitable, because it was working far away from the optimal rpms. In full scale, considering the improvements on transmitting the power stored in the arm (Mechanical Parm) are made, it is expected that a 15 m buoy will be able to generate an average of 82.5 kW i.e. 723 MWh/y, if a suitable generator is used. These figurs are based on a 60% generator efficiency, but efficiencies of 80-90% are most likely to be met in the future
3. The mooring forces have been calculated for all tests in terms of average and maximum forces. The maximum mooring calculated force is 504.2 N for the “280 mm” configuration and H6 wave condition in scale 1:25. Maximum forces are twice as bigger as average forces.
4. Areas for improvements have been investigated setting a clear line for the next investigations.

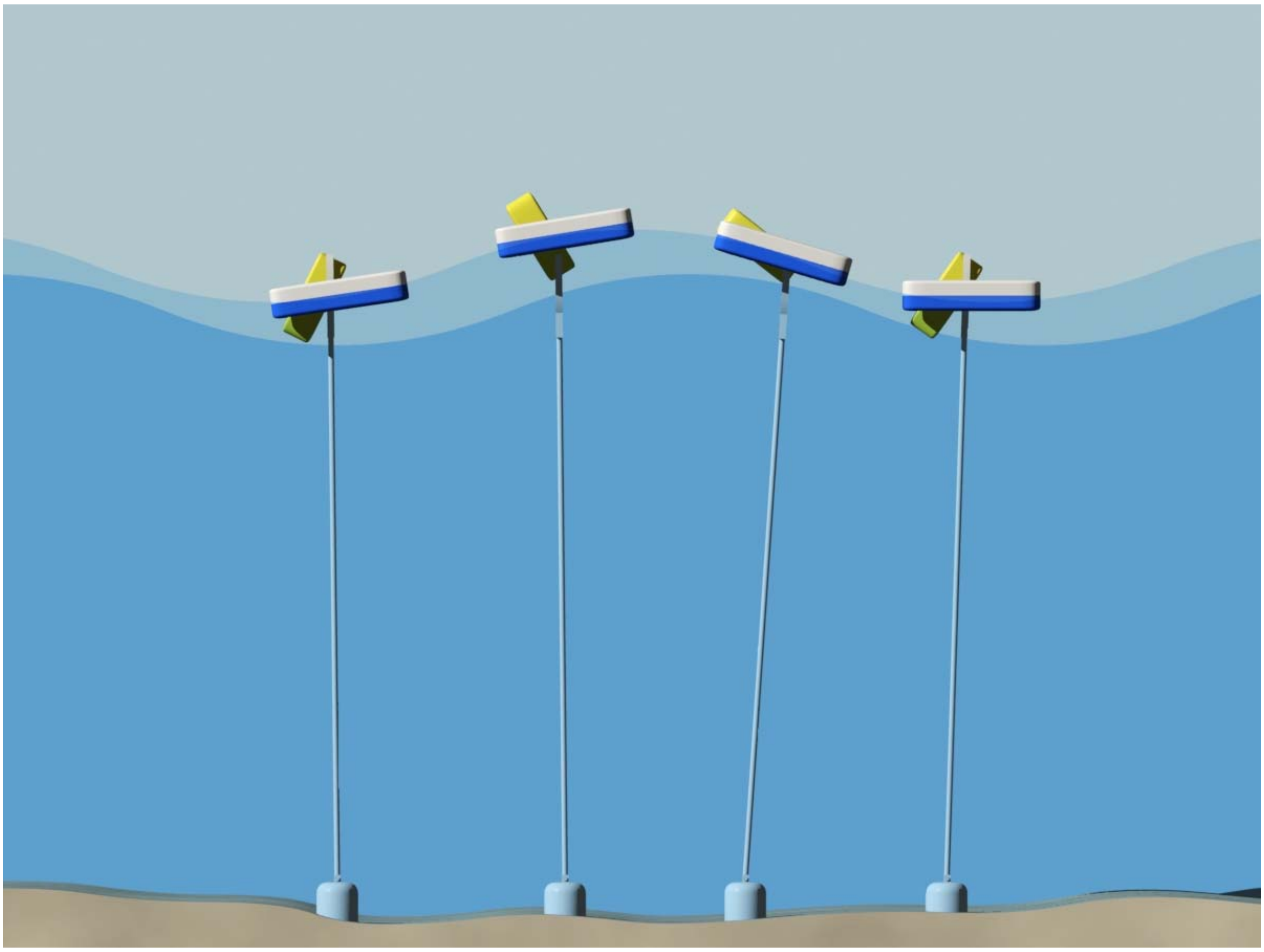
references

Rugbjerg, M. & Nielsen, K.: Kortlægning af bølgeenergiforhold i den danske del af Nordsøen. ENERGISTYRELSEN J.no. 51191/97-0014. Juni 1999.

ANNEX 1 - 3

Annex 1: Resen Waves LOPF working principle

Wave energy systems for coastal areas.



A new type of wave energy buoy with many new useful applications.

Small 1 to 5 kW buoys are currently available for:

- Powering boat tie off buoys with green electricity.
- Powering tools and cameras in the sea and on islands.
- Powering small autonomous grids in remote areas.
- Supplement or replacement of diesel generators in small grids in remote areas.
- Restoration of coral reefs and restoration of eroded shorelines.

Later when the buoys are scaled in the range from 10 to 400 kW per buoy, they can be used for:

- Grid electricity supply to villages or towns on the sea side in remote areas with poor infrastructure or a limited or unstable electricity supply.
- Tourist areas which can not expand because of limited electricity and fresh water supply, respectively. Hotels in coastal areas can even have their own wave energy electricity supply, which either replaces or supplements diesel generators.
- Utility size offshore wave farms.

The technology is based on a new type of patented electricity producing buoy which has been continuously tested in the open sea for almost a year. The electricity is produced by the vertical and horizontal movement of the buoy in the waves.

- It is simple – plug and play installation.
- Few moving parts, for high reliability.
- Low weight.
- Excellent survival properties during storms.
- Produces electricity 365 days a year, even during storms.

The power capacity can vary from 1 kW to 400 kW per buoy, which depends on the size of the buoy and the wave height (the wave climate). Each buoy can be used as a stand alone unit with a safe 12 to 24 V DC supply for charging batteries, when the buoy is next to the charging point.

Many buoys can be connected in long arrays of buoys for medium tension (11 to 15 kV) grid connection to shore.

When a wave passes a buoy, it absorbs a part of the energy of the wave and converts the absorbed energy into electricity. Therefore an array of buoys can be used for dampening the waves, to protect the coast lines, as well as produce useful electricity.

At the moment 1 to 5 kW buoys are readily available and soon 40 -, 200 - and 400 kW buoys, respectively will be available, subject to demand.

The wave energy buoys can be installed in all types of wave climates and water depths from 10 m to 50 m or more. However, when the water depth increases, the expense for installation and cabling increases as well.

How to get started?

Resen Waves systems are available and small wave energy buoys can be supplied now.

A new project could be taken through two stages to demonstrate the technology and build up a valid project.

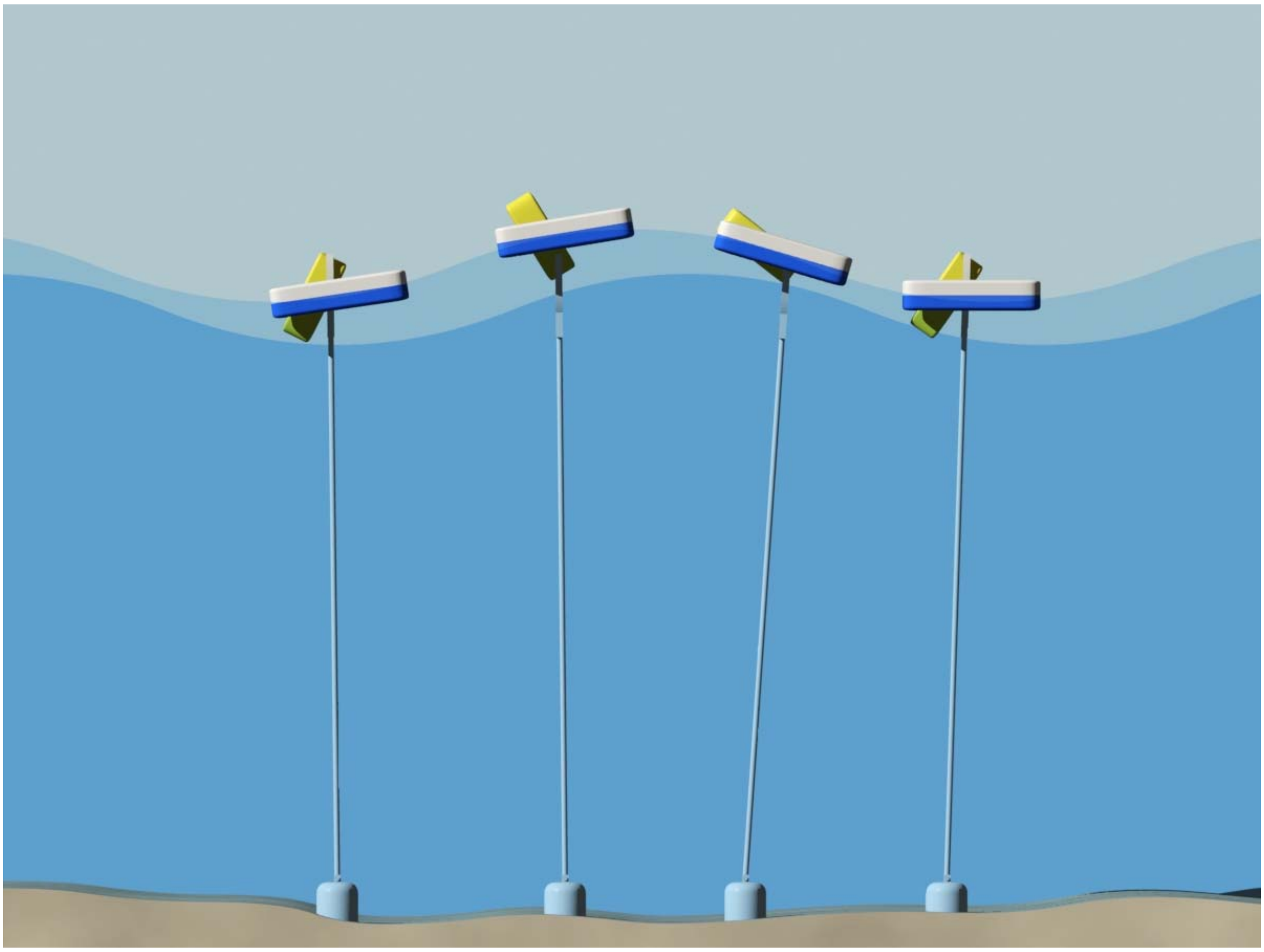
As the first stage we recommend a small demonstration project with one or two small 1 or 5 kW buoys, which provide electricity for local illumination of a pier, so everybody can see how it works. It produces electricity and it helps promote the idea among people who do not know what wave energy is and builds confidence in the technology.

The small buoys can be delivered with a lead time of 3 to 4 months. The demonstration project can be organised quickly.

Even small 5 kw buoys is good business with a fast return on investment.
Later a group of buys can always be expanded to a bigger system.

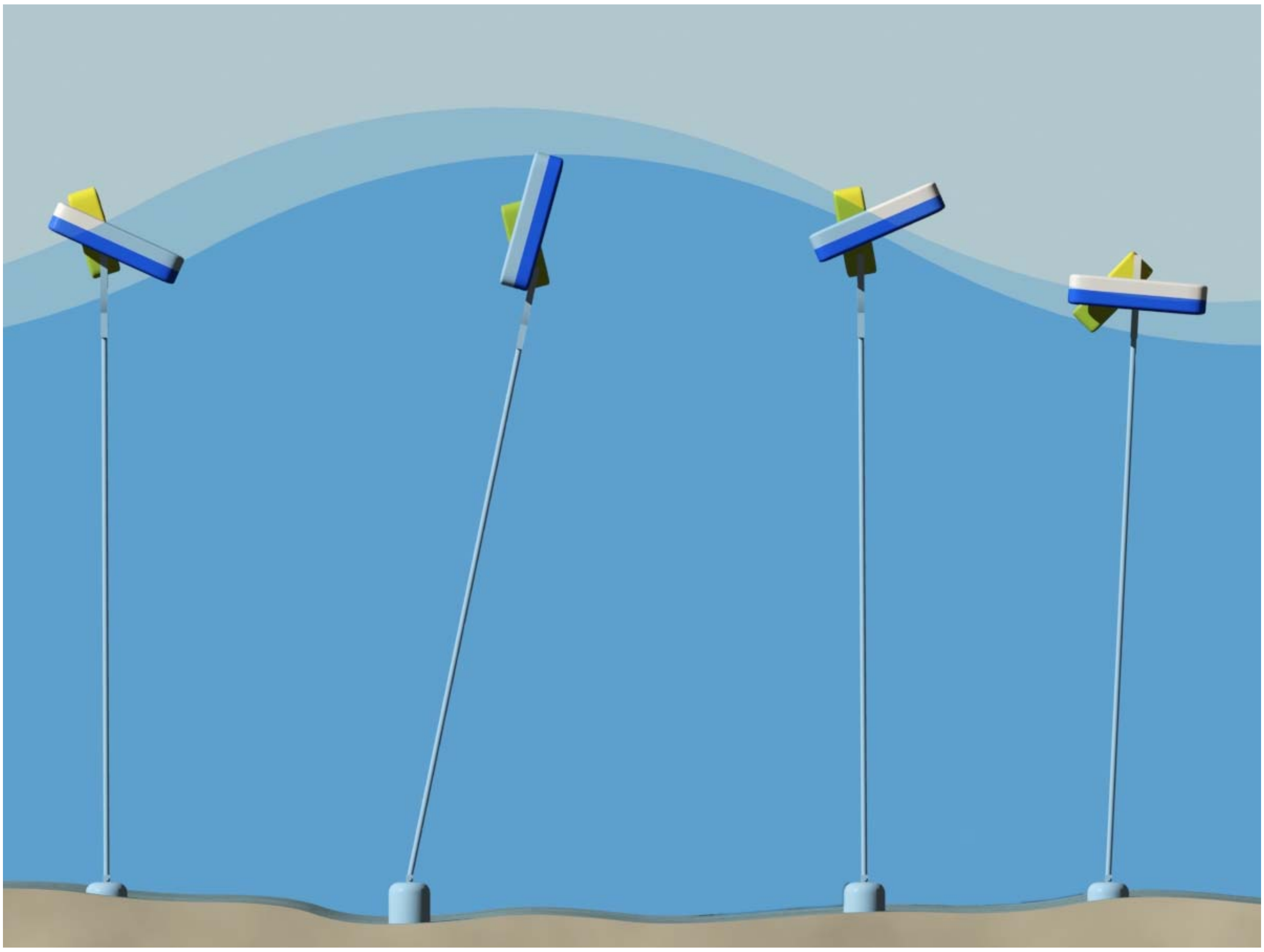
Appendix A. Technology – more detailed information on how it works

The wave energy buoy is patented and is a very simple device: that is, a horse shoe shape float with a lever in the center section that is anchored to the ocean floor. It activates as a wave lifts or pushes the buoy. The end of the lever that is anchored to the ocean floor can not move up as waves lift the buoy, causing a gearbox and generator, that is fastened on the lever, to activate as the buoy moves up and the other end of the lever, which is fixed to the sea bed, remains at a fixed elevation. The gearbox and generator is integrated within the hinge in the buoy.



This shows the buoy during a half wave cycle, from right to left, in small waves.

The relative movement between the lever (yellow part), acting also as a counter weight, and the buoy (white and blue) turns the generator and produces a burst of electric energy. This could either be, in the most simple form, a rectified DC burst, which feeds into a battery, or as an AC burst, which can be feed into a converter, which is grid connected and produces a smooth electrical output.



This shows the buoy during a half wave cycle, from right to left, in big waves.

Most traditional point absorbers have a point where the wave or tide is too big and must try to stop the surging motion of the buoy, which often destroyes the device and the mooring. This device compensates for large waves and tide in a completely different way by pivoting the buoy in combination where the lever and buoy move in opposing directions until the buoy and lever are both in a vertical position and there is no stress on components from stopping the surge or hard shock loading on the mooring lines. This relieves the vertical and horizontal thrust of the wave, so the buoy can pass through or under the big waves and pop up on the other side of the wave without having to stop any heavy moving part. Surfboards on the end of a leash do the same. The leash pulls the surfboard and the board point into the wave and easely passes through the wave without damaging the board or dragging the surfer all the way to the beach. The wave passes and the next approaching wave draws the buoy back over the anchor and the buoy folds back to the ready position.

The energy buoy, when compared to all slag moored buoy systems, also has the great advantage of being directly referenced to the sea bed with a taut line. This gives the most power output in all wave periods, as opposed to slack moored buoys with damper plates, which produces less power when the wave period increases, because the buoy is only referenced to the damper plate, which also moves up and down with the swell and reduces the actual vertical movement of the buoy.

The taut mooring also has the advantage of taking up less space in the sea per buoy, as opposed to slag moored buoys, and provides more energy to be harvested per square mile of sea.

The individual parts, generator, gearbox or buoyant buoy are all well documented standard components and technologies. Frequency converteres for grid connection, are also standard componenets, thanks to the wind turbine industry.

Annex 2: Data analysis

Calculated (and measured Tm WaveLab)				Average calculated									Calculated			Max calculated											
Hm [m] - incident	Tm [s]	Pwave[W/m]	Pwave[W]	Abs Av. Torque Gen [Nm]	Force mooring [N]		Av. Torque Arm [Nm]	Av. ElP. [W]	Av. MechP1 [W]	Av. MechP2 [W]	Abs Av [rpm]	Abs Av [Rad/s]	Eff El	Eff Mech1	Eff Mech2	Max Gen Torque [Nm]	Max Torque [Nm]		Max Angle [˚]	Min ang [˚]	Max ElP. [W]	Max MechP1 [W]	Max MechP2 [W]	Max [rpm]	Max [Rad/s]		Losses stage 3
0.173	2.800	80.7	48.4	15.775	175.021		26.253	2.325	14.878	13.234	5.3005986	0.55479599	0.048	0.307	0.273	48.484	47.440	316.267	80.593	31.101	19.447	91.765	118.746	19.234	2.013		17.56587
0.163	2.801	71.7	43.0	15.764	169.750		25.462	2.236	13.130	11.900	4.786	0.501	0.052	0.305	0.277	49.146	49.167	327.783	78.253	32.541	20.226	86.167	102.169	17.697	1.852		18.7869
0.164	2.809	72.4	43.4	15.938	169.046		25.357	1.723	12.347	10.525	4.399	0.460	0.040	0.284	0.242	48.563	49.112	327.412	74.676	33.284	13.612	84.375	88.236	17.059	1.786		16.37524
0.169	2.810	76.8	46.1	15.706	170.383		25.557	1.186	11.557	11.147	4.193	0.439	0.026	0.251	0.242	49.274	51.285	341.900	73.236	34.633	9.960	74.562	80.753	14.060	1.472		10.63754
0.149	2.515	53.7	32.2	9.995	168.070		25.210	0.474	9.431	5.128	3.274	0.343	0.015	0.293	0.159	39.637	41.273	275.154	66.803	37.558	4.336	43.476	51.020	11.098	1.162		9.245983
0.149	2.510	53.3	32.0	10.492	161.890		24.284	0.458	8.701	4.726	3.132	0.328	0.014	0.272	0.148	39.372	41.459	276.392	64.058	34.071	3.978	49.460	50.370	11.998	1.256		9.688089
0.148	2.525	52.9	31.7	10.363	161.166		24.175	0.401	8.293	4.191	2.994	0.313	0.013	0.261	0.132	37.332	41.998	279.984	62.168	34.588	3.508	45.009	36.702	11.023	1.154		9.564961
0.148	2.523	52.7	31.6	10.554	158.976		23.846	0.285	7.745	3.628	2.838	0.297	0.009	0.245	0.115	39.679	42.295	281.965	61.606	35.151	2.327	42.656	41.575	10.948	1.146		7.8667
0.120	2.240	30.7	18.4	10.794	174.194		26.129	0.383	9.679	4.443	3.436	0.360	0.021	0.525	0.241	37.709	39.267	261.780	65.138	40.190	3.498	43.054	43.116	11.023	1.154		8.624974
0.121	2.249	31.5	18.9	11.662	168.052		25.208	0.436	8.994	4.622	3.356	0.351	0.023	0.476	0.245	40.299	39.341	262.275	63.383	36.770	4.000	40.540	45.388	9.411	0.985		9.427501
0.119	2.250	30.7	18.4	11.794	167.268		25.090	0.392	8.868	4.267	3.319	0.347	0.021	0.481	0.232	38.669	38.840	258.932	62.596	36.591	3.541	41.099	40.553	7.986	0.836		9.181829
0.115	2.243	28.7	17.2	12.132	164.318		24.648	0.233	8.042	4.096	3.061	0.320	0.014	0.467	0.238	39.641	39.508	263.390	61.719	36.860	2.557	40.861	43.652	8.548	0.895		5.686779
0.121	1.962	27.6	16.5	9.284	168.410		25.261	0.219	8.872	3.349	3.405	0.356	0.013	0.536	0.202	33.873	35.032	233.546	59.604	38.323	2.318	33.998	33.376	8.286	0.867		6.536759
0.119	1.963	26.8	16.1	9.849	158.274		23.741	0.234	8.112	3.133	3.299	0.345	0.015	0.505	0.195	35.334	34.085	227.231	57.557	36.973	2.792	37.915	29.812	7.799	0.816		7.473795
0.121	1.963	27.7	16.6	9.799	155.737		23.361	0.203	7.844	3.212	3.238	0.339	0.012	0.471	0.193	36.269	34.289	228.593	57.309	36.860	2.414	33.278	40.040	7.611	0.797		6.316631
0.118	1.964	26.3	15.8	9.668	152.631		22.895	0.108	7.039	2.657	2.954	0.309	0.007	0.447	0.169	34.237	34.698	231.317	55.802	36.995	1.457	31.388	26.024	7.724	0.808		4.059198
0.096	1.683	14.7	8.8	4.833	164.813		24.722	0.012	4.905	0.675	1.934	0.202	0.001	0.555	0.076	16.316	30.091	200.606	52.945	42.035	0.184	21.680	8.411	8.698	0.910		1.716906
0.094	1.680	14.3	8.6	4.935	155.756		23.363	0.020	4.959	0.676	2.063	0.216	0.002	0.576	0.079	16.287	30.035	200.235	50.381	39.245	0.326	21.500	7.602	8.061	0.844		2.934002
0.090	1.682	13.2	7.9	4.908	156.403		23.460	0.010	4.871	0.673	2.015	0.211	0.001	0.617	0.085	16.601	29.812	198.749	50.133	39.245	0.148	20.591	5.516	7.461	0.781		1.462764
0.093	1.678	14.0	8.4	4.877	152.857		22.929	0.012	4.753	0.667	2.022	0.212	0.001	0.566	0.079	18.356	29.682	197.882	49.998	38.818	0.183	21.214	8.560	9.148	0.958		1.790633
0.066	1.403	5.9	3.5	2.538	161.245		24.187	0.003	1.898	0.200	0.750	0.079	0.001	0.540	0.057	-0.467	27.008	180.050	50.358	44.532	0.009	10.045	1.083	3.224	0.337		1.533711
0.063	1.403	5.4	3.2	2.526	151.132		22.670	0.004	1.871	0.202	0.787	0.082	0.001	0.576	0.062	0.236	25.466	169.772	48.018	41.135	0.012	12.533	1.230	3.862	0.404		2.214231

0.065	1.406	5.7	3.4	2.551	150.477		22.571	0.004	1.559	0.172	0.653	0.068	0.001	0.458	0.051	-0.757	25.540	170.267	48.063	41.270	0.011	11.779	1.192	3.787	0.396		2.595715
0.064	1.403	5.6	3.4	2.514	149.156		22.373	0.004	1.912	0.210	0.814	0.085	0.001	0.570	0.063	0.637	25.373	169.153	47.951	40.865	0.012	11.678	1.417	3.862	0.404		2.124433
					175.021	161.876						0.55479599						341.900	245.026	1.95347882							
					149.156							0.07						169.153									
0.17	2.812	81.5	48.9	18.016	259.678		72.710	1.946	38.519	12.686	5.211	0.545	0.040	0.788	0.259	48.476	136.321	486.862	84.462		15.120	238.269	105.770	17.247	1.805		15.34108
0.17	2.809	73.8	44.3	18.563	265.710		74.399	2.120	41.511	13.273	5.445	0.570	0.048	0.938	0.300	47.081	139.089	496.747	82.842		15.042	226.505	95.165	16.497	1.727		15.97529
0.17	2.808	78.9	47.3	18.884	265.341		74.295	1.863	38.635	12.706	5.085	0.532	0.039	0.817	0.269	47.404	139.721	499.002	82.707		12.079	203.305	92.270	14.060	1.472		14.6601
0.18	2.810	84.9	51.0	18.550	257.541		72.111	1.482	35.297	11.356	4.734	0.495	0.029	0.693	0.223	49.225	141.188	504.243	82.482		11.748	213.774	92.657	13.910	1.456		13.04622
0.140	2.258	42.6	25.5	12.743	257.702		72.156	0.478	29.320	5.556	4.032	0.422	0.019	1.148	0.218	43.874	102.143	364.798	64.598		5.483	115.229	54.752	8.886	0.930		8.609613
0.140	2.522	47.5	28.5	10.735	249.164		69.766	0.369	24.814	4.339	3.350	0.351	0.013	0.871	0.152	43.026	108.236	386.557	67.612		6.204	114.915	48.797	8.811	0.922		8.505524
0.140	2.520	47.4	28.5	10.450	249.378		69.826	0.323	23.875	4.124	3.218	0.337	0.011	0.839	0.145	44.896	107.939	385.496	67.208		5.851	110.493	53.385	7.836	0.820		7.821444
0.140	2.522	47.5	28.5	10.863	245.068		68.619	0.268	22.832	3.915	3.097	0.324	0.009	0.801	0.137	39.608	106.546	380.520	66.375		4.313	100.327	39.325	7.386	0.773		6.852516
0.14	2.102	37.2	22.3	7.745	244.109		68.351	0.088	20.114	2.341	2.849	0.298	0.004	0.902	0.105	25.837	91.036	325.127	55.870		1.206	71.265	16.122	8.548	0.895		3.754638
0.13	2.248	34.9	20.9	9.172	254.950		71.386	0.189	22.635	2.928	3.100	0.324	0.009	1.083	0.140	34.477	91.463	326.653	58.862		3.044	91.682	28.433	8.324	0.871		6.457834
0.13	2.237	35.3	21.2	9.383	256.641		71.860	0.191	22.544	2.914	3.064	0.321	0.009	1.064	0.138	36.790	92.912	331.827	59.132		3.062	85.195	32.257	10.348	1.083		6.560337
0.13	2.244	35.6	21.4	9.853	251.924		70.539	0.166	21.904	3.048	3.043	0.318	0.008	1.025	0.143	35.541	90.683	323.866	58.232		2.662	89.468	23.429	8.586	0.899		5.447942
0.12	1.702	24.0	14.4	6.268	238.272		66.716	0.021	16.523	1.224	1.965	0.206	0.001	1.149	0.085	15.174	89.791	320.682	50.516		0.207	71.338	10.100	8.923	0.934		1.690241
0.11	1.923	23.5	14.1	7.271	235.582		65.963	0.036	17.650	1.820	2.591	0.271	0.003	1.251	0.129	21.546	87.543	312.655	52.338		0.528	66.325	12.803	8.399	0.879		1.954097
0.11	1.485	17.4	10.4	4.635	233.303		65.325	0.006	12.779	0.776	1.866	0.195	0.001	1.225	0.074	7.072	80.039	285.854	48.626		0.034	60.799	7.186	8.436	0.883		0.755763
0.09	1.686	12.4	7.4	4.704	232.391		65.070	0.005	11.520	0.770	1.690	0.177	0.001	1.547	0.103	7.076	81.284	290.299	48.153		0.028	50.176	6.830	6.636	0.695		0.632518
					265.710	249.797	74.399	2.325		13.273		0.570	0.052	1.547	0.300			504.243	376.324	1.897721408				19.2	2.0		18.8
					232.391		65.070	0.003		0.172		0.177	0.001		0.051			285.854						3.2	0.3		0.6
						87.921		0.523		4.538					0.162				131.298								

Annex 3: Wave Measurements

Wave measurements have been realized with three aligned wave gauges in order to be able to separate incident and reflected waves. The target waves where in the range 0.085 to 0.198 m in 0.68 m water depth. Mechanical problem with the wave generator usually do not allow the accuracy to be better than ±0.02 m from the target wave height and for periods higher than 2.3 s.

Results from the reflection analysis with Wavelab where use only to calculate the reflection coefficient for each test. The wave height was instead calculated by the time series analysis of the signal and from this the reflected wave was subtracted. Singularities have been noticed for H5, featuring target H=0.17 m and T=2.52 s. In this case the reflection was lower than expected; in the figure below we can see the total measured wave height (incident +reflected) plotted depending on measured reflection coefficient. The red circle highlights the calculated reflection for the tests with H5 and in blue the expected reflection for the same tests. This difference has been considered as an error and a regression analysis with the rest of the data was conducted on order to extrapolate the reflection coefficient for H5.