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EXPERIMENTAL STUDY OF THE WEPTOS WAVE ENERGY CONVERTER

Arthur Pecher
Aalborg University
Aalborg, Denmark

Jens Peter Kofoed
Aalborg University
Aalborg, Denmark

Tommy Larsen
WEPTOS A/S
Juelsminde, Denmark

Tanguy Marchalot
Aalborg University
Aalborg, Denmark

ABSTRACT

This paper presents the power performance results of the experimental study of the WEPTOS wave energy converter (WEC), a novel device that combines an established and efficient wave energy absorbing mechanism with a smart structure that can regulate the amount of incoming wave energy and reduce loads in extreme wave conditions. This V-shaped floating structure absorbs the energy of the waves through a multitude of rotors, the shape of which is based on the renowned Salter's Duck. These rotors pivot around a common axle, one for each leg of the structure, to which the rotors transfer their absorbed wave energy and which is connected to a common power take off system (one for each leg). The study investigates the performance of the device in a large range of wave states and estimates the performance in terms of measured mechanical power of the WEPTOS WEC for two locations of interest, a generic offshore location in the Danish part of the North Sea and the location of the Danish wave energy centre (DanWEC) in front of Hanstholm harbour.

NOMENCLATURE

AEP	Annual energy production	[GWh]
Contrib	Contribution to the available wave power	[-]
H_s	Significant wave height	[m]
H_{m0}	Estimation of the significant wave height	[m]
PTO	Power take off	
P_{mech}	Average mechanical power	[kW]
Prob	Probability of occurrence	[-]
P_{wave}	Wave power level	[kW/m]
T_p	Peak wave period	[s]
G	Peak enhancement factor (JONSWAP)	
S	Directional spreading factor	
S_p	Wave steepness	
WEC	Wave energy converter	
WS	Wave state	
η	Non-dimensional performance	[-]
ω	Rotational speed of the axle	[RPM]
τ	Torque measured on the axle	[Nm]

INTRODUCTION

The WEPTOS WEC is a floating structure, composed of two symmetrical frames ("legs") that support a multitude of identical rotors, which absorb the energy from the waves and transfer it to a rotating axle.

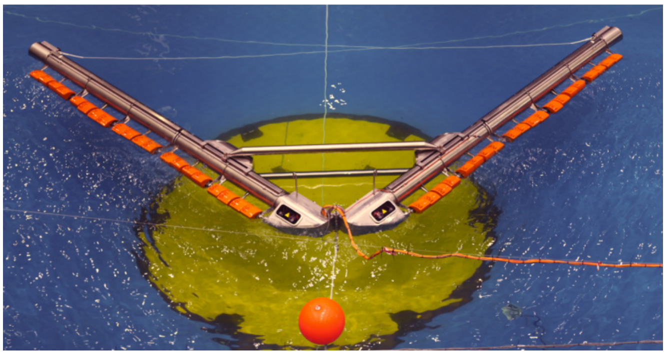

Fig. 1: Picture of the WEPTOS prototype during lab test.

The shape of these rotors is based on Salter's duck WEC, which was invented in 1974 and was then subject to intensive research [1]. All of the rotors connected to the same leg are driving a common axle. These rotors only engage (or transmit power) with the axle during their upstroke pivoting motion through a ratchet mechanism (Fig. 2). These two common axles (one for each leg of the device) are each connected to an individual power take off (PTO) system, which is located in the front compartments and consists of an electrical motor. The torque has been measured between the axle and the PTO system.

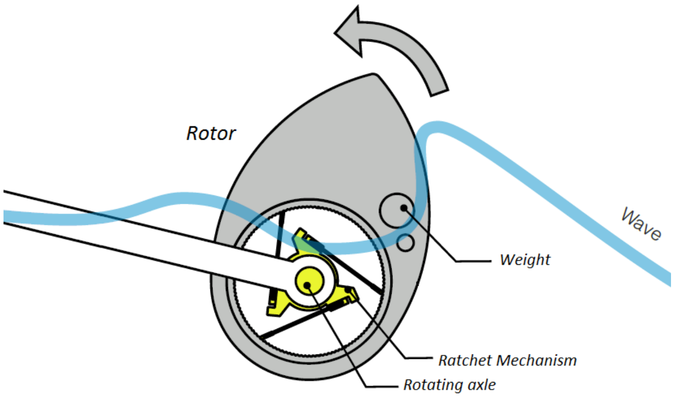

Fig. 2: Side view illustration of the working principle of the ratchet mechanism of each rotor.

Another particularity of this concept is that the opening angle between the two main legs is adaptable, as it is regulated by the position of the transversal beams on the legs. This allows the device to adapt its configuration relative to the wave conditions, improving its survivability by significantly reducing the mooring forces and structural bending moments during storm conditions [2]. Having an opening angle results also in a smoother power transfer to the power take off (PTO), as the rotors absorb and transfer their energy at different time intervals. This keeps the axle in constant rotation and avoids extreme instantaneous transfer of energy to the PTO, which results in a lower installed power for an identical average power and thereby a high load factor [3].

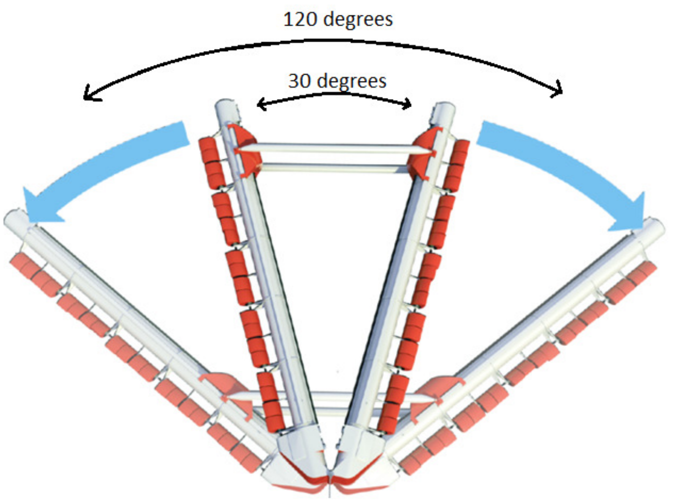

Fig 3: Illustration of the adaptable opening angle between 30 and 120 degrees.

This paper presents the results from laboratory testing in a large 3-D wave basin using an advanced prototype concerning the power performance of the device for a wide range of wave conditions and some alterations to the wave conditions. These results are then used for estimations regarding the performance of the WEPTOS WEC for two locations of interest, a generic offshore location in the Danish part of the North Sea and Hanstholm harbour, location of the Danish wave energy centre.

EXPERIMENTAL SETUP

The WEPTOS prototype is a very realistic scale model representing a real sea power producing WEPTOS machine, as it includes all main elements of the real target WEPTOS machine, even the two electrical motors acting as PTO system. It performed very well during all the tests that have been performed in the CCOB facility in Santander, Spain [4], resulting in a vast amount of high quality data and enabling a good representation of the performance of the device in a wide range of wave conditions.

The WEPTOS prototype had 2 legs of about 7.4 m, each holding 20 rotors of 0.24 m width, a chord of 0.326 m and a diameter around their axle of rotation of 0.2 m. The whole prototype weighted around 1150 kg.

All the various instruments doing measurements on the device were communicating with a main (onshore) PLC by Profibus and were connected together with the wave gauges to a central Data Acquisition (DAQ) system (NI 6225).

Torque meters were mounted directly on the power transmission axle of each leg of the superstructure, at the connection of the axle with the gear of 1:3 of the PTO system, providing a good and direct measurement of the torque.

The two electrical motors used to simulate the PTO system were connected through a Profibus connection to the main PLC, which regulated the PTO loading and acquired some useful data such as the rotational speed.

The vertical and horizontal structural bending moments in the legs were measure by strain gauges, which were installed on a flange located between the second and third sections of each leg (between the eighth and ninth rotor starting counting from the front).

The mooring line was equipped with a force transducer, which was located at the connection of the hawser with the WEPTOS prototype.

The wave basin was equipped with 9 wave measuring probes, which enabled to measure the wave height and wave period, together with other useful wave parameters, by taking the 3D character of the waves into account. The wave characterizing parameters (H_{m0}, T_p and P_{wave}) were calculated by 3D wave analysis in Wavelab.

TEST METHOD

Definitions and terminology

In each of the 14 production wave state in which the prototype has been tested, the PTO loading has been optimized in order to obtain a best non-dimensional performance (η), which is the ratio between the mechanical power (P_{mech}) measured on the axle of each leg divided by the wave power (P_{wave}) set to the combined width of all the rotors:

$$\eta = \frac{P_{mech_{Starboard}} + P_{mech_{Port}}}{Pwave\ .\ 2\ .\ 20\ .\ 0{,}24} \qquad (1)$$

This definition presents the non-dimensional performance independently from the opening angle, making the η of the WEPTOS prototype obtained with different opening angles comparable.

The wave energy contribution (Contrib) of a certain wave condition (e.g. bin of the scatter diagram) represents the ratio of the average available energy of a certain wave condition relative to the overall and can be calculated by:

$$\text{Contrib}_{\text{bin}} = \frac{(\text{P}_{\text{wave}})_{\text{bin}} \cdot \text{Prob}_{\text{bin}}}{\sum_{\text{bin}=1}^{n} ((\text{P}_{\text{wave}})_{\text{bin}} \cdot \text{Prob}_{\text{bin}})} \quad (2)$$

The term "scaling ratio" refers to the difference in physical size between the WEPTOS prototype, as used in the lab, and a greater version of the WEPTOS machine, which could be installed at a given offshore site [5]. This same scaling ratio is used to "down-scale" the wave conditions of the corresponding location to the current WEPTOS prototype. These wave parameters (e.g. H_{m0} and T_p) and the physical dimensions of the device can be scaled following Froude's scaling law [6].

The overall η can be calculated based on the η of the individual wave states, given in Eq. (3) [7]:

$$\eta_{\text{overall}} = \sum_{i=1}^{n} \eta_i \,.\, \textbf{Contrib}_i \quad (3)$$

The mechanical power output (P_{mech}) for a certain wave condition corresponds to multiplying the average available wave power (using the deep water approximation, P_{wave}=0,49.T_p.H_{m0}^2 and $T_e = T_p/1.15$) to the η of the device in those wave conditions.

$$\text{P}_{mech_i} = \text{P}_{wave_i} \cdot \eta_i \quad (4)$$

An overall average mechanical power production of the machine can be found by taking the sum of the multiplication of the mechanical power production of the machine in every wave condition by the probability of occurrence of the corresponding wave condition.

$$\textbf{P}_{\textbf{average}} = \sum_{i=1}^{n} \textbf{P}_{\textbf{mech}_i} \,.\, \textbf{Prob}_i \quad (5)$$

From the average power production of the WEC, the yearly total converted energy or annual energy production (*AEP*) can be calculated by multiplying the average power production by the hours in a year (≈ 8760) [8].

$$AEP = \text{P}_{\text{average}} \,.\, 8760 \quad (6)$$

The Load Factor (*LF*) represents the average usage of the installed generator capacity and corresponds to the ratio between the overall average mechanical power and the maximum mechanical power in any wave conditions of the scatter diagram.

$$LF = \frac{\text{P}_{\text{average}}}{\text{maximum}\,(\text{P}_{mech})} \quad (7)$$

Tested wave conditions

The main aim of the experimental tests was to assess the power performance of the device and the mooring forces and structural bending moments, while this paper only focuses on the power production. The wave states (WS) used for the lab tests are based on the wave conditions of Anholt P2 (WS 1-5) [9] at a scaling ratio of 1:8.33, a location where an offshore wind farm is planned to be installed, and a generic offshore location in the Danish part of the North Sea (WS 6-10) [10] at a scaling ratio of 1:23.4. In order to widen the range of wave conditions, 4 other wave states were added (WS 11-12, 0A and 0B). These wave states represent the wave conditions in which a WEPTOS machine would operate and will thereby be referred to as "production" wave states.
In all the wave states, the performance has been analysed with long-crested irregular waves (JONSWAP spectrum with a peak enhancement factor of 3.3) over time spans of 20 min. Tests with 3D waves or extreme wave states were performed over 45 min.

Constant and linear PTO loading

The performance of the WEPTOS prototype was first investigated with a constant PTO loading in the various production wave states and afterwards elaborated with a linear PTO loading in some of the wave states, due to time limitations. The constant PTO loading consisted of having a fixed target torque (τ) value on the axle throughout the whole test, which can be seen in Fig. 4. The recorder torque resulted relatively scattered, but still around the target value.

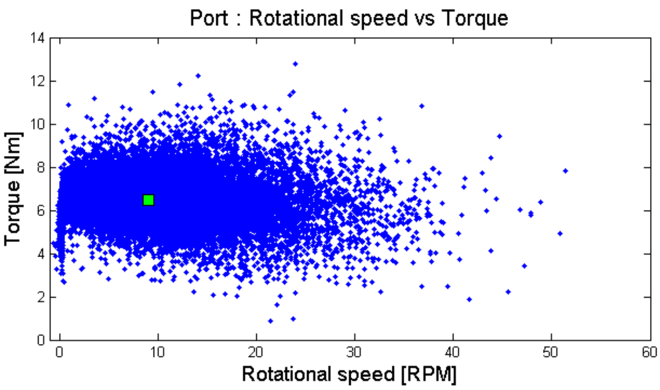

Fig. 4: Plot of τ versus *ω* for port side constant PTO loading of 6 Nm in wave state 3 and opening angle of 90 degrees. The green dot represents the average ω and τ.

The linear PTO loading consisted of having a target torque value being proportional to the rotational velocity of the axle

(ω) (see Fig. 5), which was averaged over a window of the past 0.4 s.

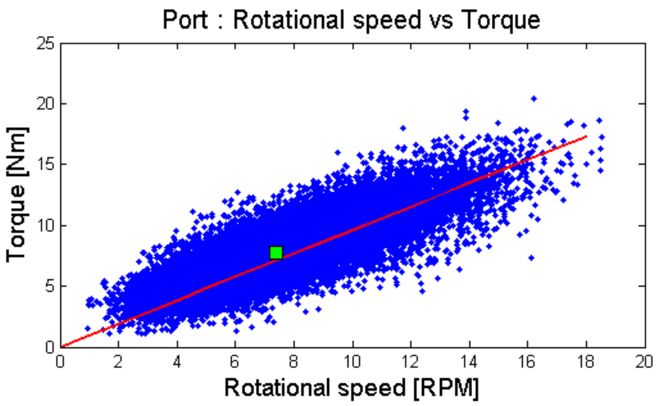

Fig. 5: Plot of τ versus ω for port generator having a linear PTO loading in wave state 3 and opening angle of 90 degrees. The green dot represents the average ω and τ and the red line the trend line passing through zero.

A significant difference in range of τ and ω can be seen between the constant and linear PTO loadings in the optimal setups in wave state 3, even if the average values of τ and ω are approximately equal. For a constant PTO loading, on each axle τ ranges between 0 and 12 Nm and ω between 0 and 50 RPM; while, for a linear PTO loading the τ increases from 1 up to 19 Nm, while the ω is limited between 2 and 20 RPM. With the linear PTO loading, ω also never drops to zero.

Alterations to the wave conditions

For two specific production wave states (WS 2 and 4), the influence of the peak enhancement factor of the JONSWAP spectrum and directional spreading has been analysed. The peak enhancement factor (G) of the JONSWAP spectrum has been set to 1 and 7, which broadens and narrows the spectral shape relative to reference G of 3.3. 4 different wave spreading factors (S) were used (99, 10, 5 and 2), where 99 (is the reference) stands for long crested waves, and 2 for full 3D wave conditions [11].

The filenames that contain *G* or *S*, mention the corresponding value, otherwise it can be assumed that the characteristics are unchanged. The tests with the alterations to the wave conditions were performed with the optimal constant PTO loading that was found in the reference case. An optimization of the PTO loading for each specific wave conditions might possibly have resulted in smaller performance losses relative to the reference.

Performance estimations

The estimation of the performance of a WEPTOS machine at Hanstholm harbour and in the Danish part of the North Sea is based on the lab tests results and more particularly, on the performance curve as given in Fig. 8. The corresponding η to the wave period of each bin of the scatter diagram is found by interpolation on the performance curve.

A table summarizing the performance is given for every location. In the upper part of the table, the scaling ratio of the WEPTOS device is given relative to the WEPTOS prototype (absolute) and relative to the smallest absolute scaling ratio for that location (relative). Then, values are organised for 2 different load factors (*LF*). For each *LF* and scaling ratio, the overall η, the average and max Pmech and annual energy production (*AEP*) is given. The relative *AEP* for each case is than given relative to the *AEP* of the lowest scaling ratio for that location. In the last part of the table, the η and P_{mech} is given for each wave state.

TEST RESULTS

Opening angle

In Fig. 6, the non-dimensional performance (η) is given for different opening angles of the WEPTOS prototype and in different wave states, with a constant PTO loading.

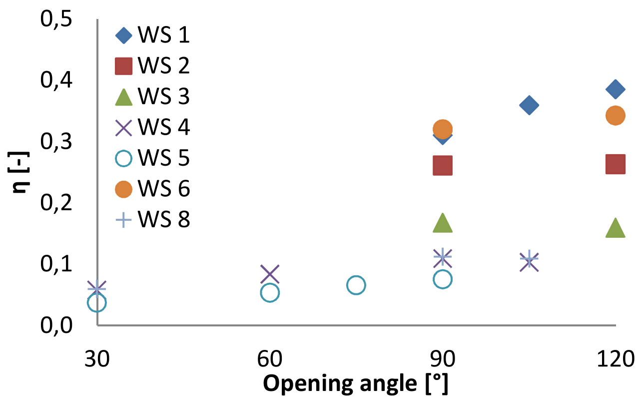

Fig. 6: η for different opening angles of the WEPTOS prototype and wave states with a constant PTO loading.

In the WS corresponding to the smallest wave conditions (WS 1 and 6), the η is the highest for an opening angle of 120 degrees. However, for larger wave conditions the WEPTOS prototype performs the best with an opening angle of 90 degrees, as the performance decreases for smaller and larger opening angles. This indicates that restricting the opening angle of the device to maximum 90 degrees will only have a small impact on the overall performance.

Wave height and period dependency

In Fig. 7, the influence of the wave steepness (S_p), corresponding to the ratio of the wave height to the wave length (based on T_p), on η is represented. Several wave conditions were used having a similar H_s or T_p: WS 4, 8 and 11 have a T_p of ~ 1.72 s; WS 9 and 12 have a T_p of 2.03 s; WS 2, 7 and 11 have a H_s of ~ 0.085 m and WS 8 and 12 have a H_s of 0.128 m. For the markers with a constant T_p, the H_s had to be modified in order to change S_p and vice versa for the H_s.

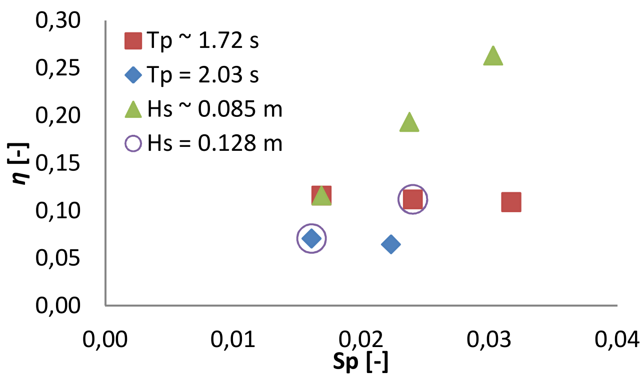

Fig. 7: Representation of the influence of T_p and H_s on η.

T_p is clearly the most influential, as the variation of η in between two points having the same H_s but different S_p is increasing significantly with decreasing T_p. While the η decreases only slightly with an increasing H_s. Therefore the η for various wave conditions will be obtained based on T_p.

Non-dimensional performance of the WEPTOS prototype

The highest η that has been obtained for the various production wave states are given separately for the linear and constant PTO loading in Table 1 and represented in Fig. 8.

Table 1: Overview of the η of the WEPTOS prototype in the production wave states, with linear and constant PTO loading.

WS	Target Hs	Target Tp	Opening	PTO loading Constant	PTO loading Linear
	[m]	[s]	Angle [°]	η [-]	η [-]
1	0.047	1.06	120	0.39	0.43
2	0.084	1.28	90	0.26	0.32
3	0.118	1.51	90	0.17	0.21
4	0.165	1.72	90	0.11	0.11
5	0.212	1.92	90	0.08	0.06
6	0.043	1.16	120	0.34	
7	0.085	1.45	120	0.19	
8	0.128	1.74	90	0.11	
9	0.171	2.03	90	0.06	0.06
10	0.214	2.32	90	0.03	
11	0.085	1.72	120	0.12	0.13
12	0.128	2.03	90	0.07	
0A	0.04	0.97	120	0.48	0.37
0B	0.035	0.9	120	0.57	

Based on these performance results and some estimated values for wave conditions falling outside the range of the tested wave conditions, a performance curve is established. This performance curve is used to determine the η of WEPTOS machine in the wave conditions of locations of interest, by scaling the corresponding wave conditions down.

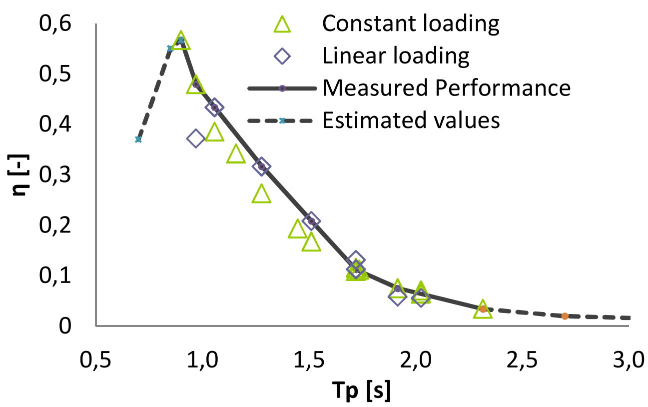

Fig. 8: Presentation of η with a constant and linear PTO loading, together with the performance curve.

In general, the η decreases with increasing T_p and the prototype performed better with a linear PTO damping than with a constant PTO loading, except in the highest and lowest wave states. The disability of the linear PTO loading to perform better in the lower wave states could have been due to its fixed averaging window of 0.4 s of the ω, making the resulting PTO loading being suboptimal. In WS 5, large scatter was encountered in the ω-τ combinations, which indicates inconsistent PTO loading and probably is the reason why the linear PTO loading was performing less well. However, this indicates that the PTO loading can still significantly be optimized which will result in even better performances.

The middle part of the performance curve (full-line) is based on the measured values while the both extremities of the performance curve are based on estimations (dashed line). A higher η could possibly still be found at a lower T_p, but these wave conditions could not been realized in the lab, therefore a (conservative) decreasing curve is used.

A two dimensional performance curve (η, T_p) was decided to be used for the estimation of the performance of the device and is especially based on the results of wave state 1 to 5, as in general the η for a constant PTO loading was found to be higher for the wave states 6 to 10 (describing the Danish part of the North Sea) than for wave state 1 to 5 (based on Anholt P2). As the scaled wave conditions from other locations of interest would be closer to the wave conditions of the North Sea, it is conservative to take the performance of WS 1 to 5 as the reference. It explains why the performance curve does not pass through the highest measured performance at a T_p of 1.72 s.

Alterations to the wave conditions

The next figure presents the impact of the spreading factor (S) and a peak enhancement factor (G) on η. The reference values of G and S are 3.3 and 99 and the values corresponding to the alterations are mentioned in the name.

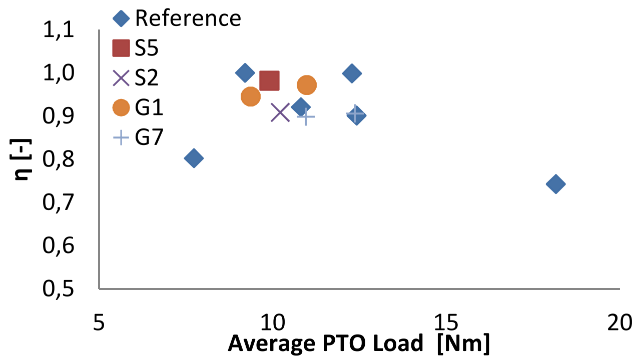

Fig. 9: Relative impact of the spectral shape and directional spreading in WS 2 on η with opening angle of 120° and constant PTO loading.

In general the influence of the spectral shape and directional spreading appears to be very low in small wave conditions. For a broader spectrum (G7), the performance is roughly the same while it decreases by approximately 10 % with a more focused peak period (G1). Similarly for the directional spreading, an S-factor of 5 does not seem to have a real impact on the performance, while a decrease of about 10 % can be expected for a S-factor of 2 (full 3D waves). However, the small drop in performance for the marker of the reference case in the middle shows the uncertainty involved for single measurement tests. Therefore, in general it can be expected that the influence of the spectrum width and directional spreading is relatively small in the smaller wave conditions.

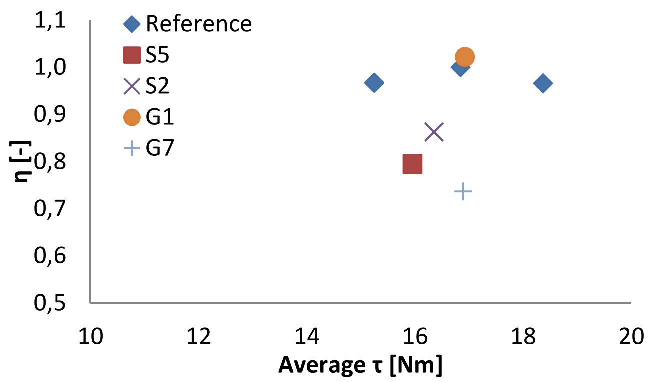

Fig. 10: Relative influence on η of the spectral shape and directional spreading in WS 4 with constant PTO loading.

The results in WS 4 follow the same trend but are more pronounced than in WS 2. A broader spectral shape (G1) does not seem to have a great influence on the η. The directional spreading has in all the cases diminished the wave conditions by about 20 % relative to the long-crested wave conditions.

PERFORMANCE ESTIMATIONS

Hanstholm harbour

The wave data of Hanstholm harbour (Denmark) has been gathered by a buoy at a mean water depth of 18 m in front of the harbour and corresponds to an average wave energy potential of 6.1 kW/m. In Fig. 11, the contour plot of the scatter diagram and of the contribution of the wave conditions is given. The majority of the waves range from 0 to 3 m in H_s and 3 and 7 s of T_p, while in average most of the wave energy lies in the wave conditions between 1.5 and 3.5 m and between 5 and 8 s.

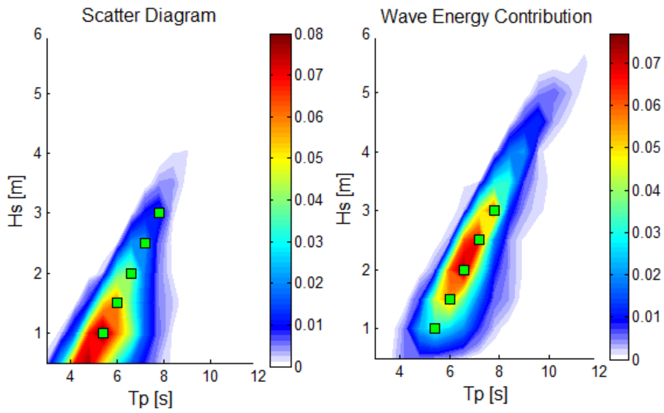

Fig. 11: Scatter diagram and wave energy contribution representation of Hanstholm, with wave states (green dots).

The η for the different wave states of Hanstholm at different scaling ratios is given in the next figure. For the different scaling ratios, the outermost left marker corresponds to WS 1, increasing to the left and finishing with WS 5 at the right end.

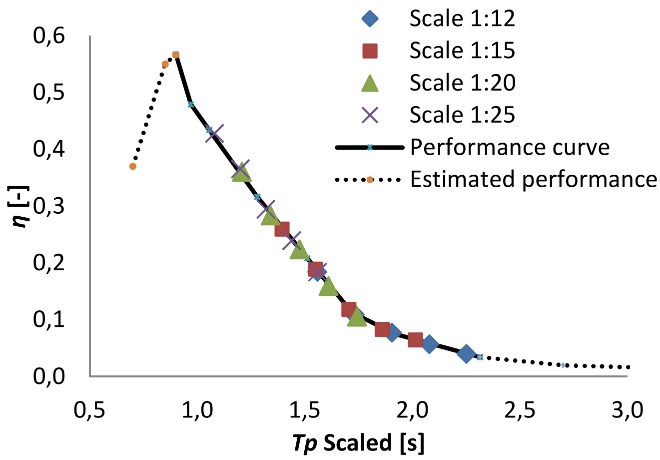

Fig. 12: η for the wave states characterizing Hantholm harbour and for 4 scaling ratios of the WEPTSOS machine.

As the scaling ratio increases, the scaled wave period of the wave states decreases. This results mainly in an increase in corresponding η for the given wave state as they slide up the performance curve. Based on these values, power production

estimations have been made and are presented in**Fejl! Henvisningskilde ikke fundet.**

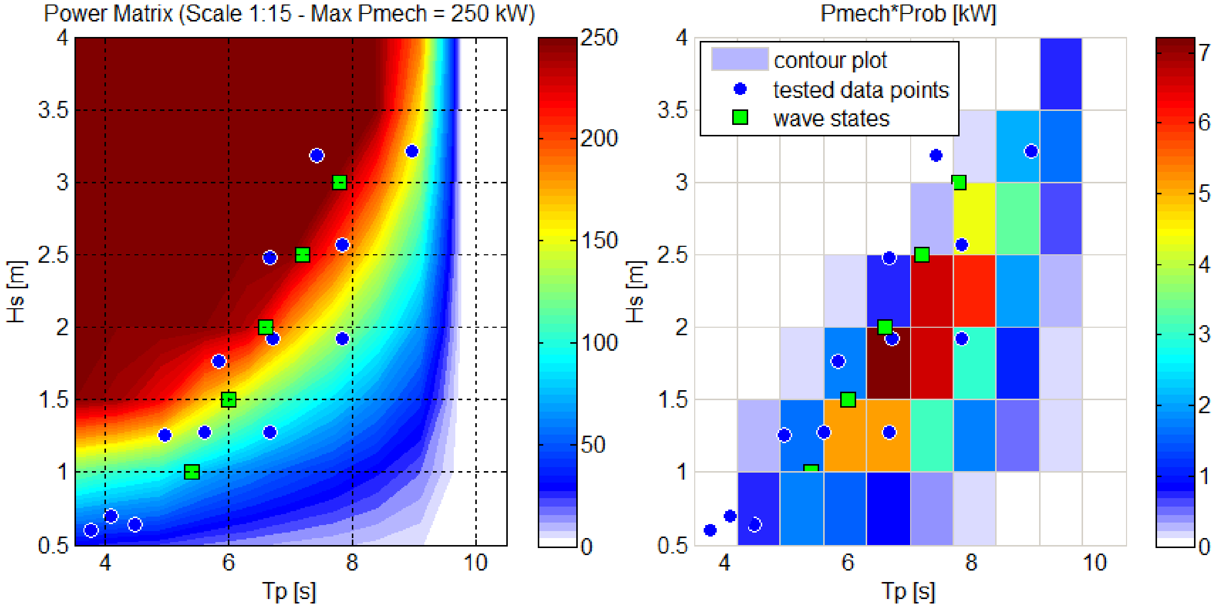

Figure 13: Power matrix and P_{mech}*Prob plot of the WEPTOS WEC at a scaling ratio of 1:15 with a maximum P_{mech} of 250 kW and installed in Hanstholm.

Table 2: Estimation of the WEPTOS performance at Hanstholm for 4 scaling ratios and for 2 load factors.

Absolute & relative scale			**12***	1	**15**	1.25	**20**	1.67	**25**	2.08
Length of a leg [m]			89		111		148		185	
Rotor width & chord [m]			2.9	3.9	3.6	4.9	4.8	6.5	6.0	8.2
Combined rotor width [m]			115		144		192		240	
LF [-]			**0.33**	**0.42**	**0.33**	**0.42**	**0.32**	**0.41**	**0.32**	**0.39**
Overall η [-]			0.08	0.08	0.12	0.12	0.19	0.18	0.25	0.23
Average Pmech [kW]			58	56	108	103	226	213	370	344
Max Pmech. [kW]			176	132	330	247	699	524	1166	875
AEP [GWh]			0.5*	0.5	0.9	0.9	2.0	1.8	3.2	3.0
Relative AEP to ref. [-]			1.00	0.97	1.87	1.78	3.91	3.68	6.40	5.96
Wave State	Hs	Tp	η	*Pmech*	η	*Pmech*	η	*Pmech*	η	*Pmech*
	[m]	[s]	[-]	[kW]	[-]	[kW]	[-]	[kW]	[-]	[kW]
1	1	5.4	0.18	49	0.26	86	0.36	159	0.43	236
2	1.5	6	0.11	73	0.19	158	0.28	316	0.37	508
3	2	6.6	0.08	99	0.12	189	0.22	476	0.29	784
4	2.5	7.2	0.06	124	0.08	226	0.16	578	0.24	1085
5	3	7.8	0.04	134	0.06	274	0.11	598	0.18	1302

*reference for the relative values

A WEPTOS device at a relatively small scaling ratio of 1:15, corresponding to an active width (combined rotor width) of 144 m, and located in a relatively low wave energy resource (6.1 kW/m) will already produce a substantial amount of power at a high *LF*. It is estimated to generate, with a 250 kW PTO capacity, in average 103 kW, resulting in an *AEP* of 0.9 MWh and a *LF* of 0.42. The high *LF* results from the adaption of the opening angle in the greater wave conditions, which reduces the exposure to the incoming waves and thereby stabilises P_{mech}. Note that the *LF* of an average Danish wind turbine is around 0.2 – 0.25 [13].

The η and *AEP* increases significantly with the scaling ratio, as they increase sixfold by only doubling the size, which can be noticed between scaling ratio 1:25 and 1:12. This indicates that the *AEP* will benefit significantly of having a larger structure, as, in the tested range and performance-wise, no optimal scaling ratio has been found.

The impact of limiting the maximum P_{mech} appears to have a relatively small impact on the *AEP*, but increases significantly the *LF*, as a drop in *AEP* of 5 % results in an increase of 27 % in *LF* for scaling ratios of 1:15.

The average P_{mech} and indirectly η for different scaling ratios and wave states are presented in Fig. 14.

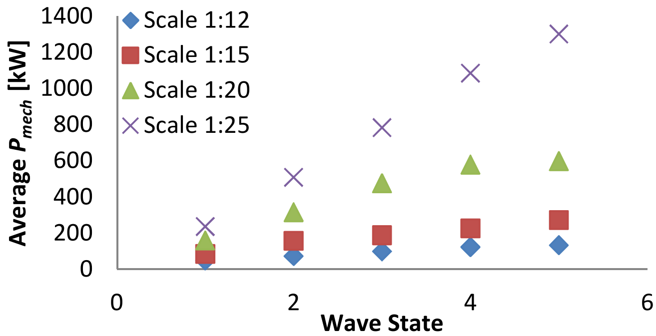

Fig. 14: Average P_{mech} of the WEPTOS for the 5 WS of Hanstholm harbour and for 4 scaling ratios.

It can be noticed that the relative difference in P_{mech} and η between wave states, increases more significantly for higher scaling ratios of the device and that The P_{mech} in WS 4 and 5

seems to be almost similar for scaling ratios of 12, 15 and 20. This explains the high *LF*, as there is no special need for a large generator capacity for in the larger wave conditions.

Danish part of the North Sea

The generic location Point 3 in the Danish part of the North Sea, for which the *AEP* of most Danish developing WEC are estimated, has an average wave power level is 16.3 kW/m and is located about 150 km from shore at a water depth of 39 m [14]. In Fig. 15, the scatter diagram and wave contribution is given for this location, on which can be seen that the most frequent wave conditions are between 0 – 2 m H_s and 4 -7 s T_p, while the most wave energy contributing wave conditions range from 2 up to 5 m H_s and 7 to 11 s T_p.

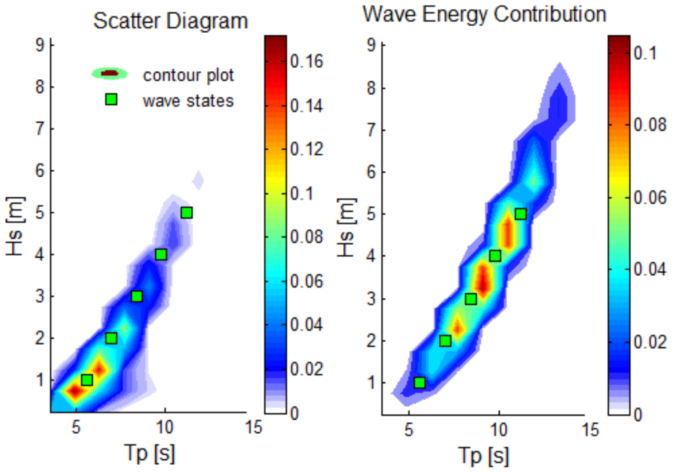

Fig. 15: Scatter diagram and wave energy contribution representation of the Danish North Sea with the wave states (green dots).

Fig. 16 presents the η of the WEPTOS device given for different scaling ratios of the wave states characterizing the Danish part of the North Sea [3]. For the different scaling ratios, the outermost left marker corresponds to WS 1, which increases to the left and finishes with WS 5 at the right end.

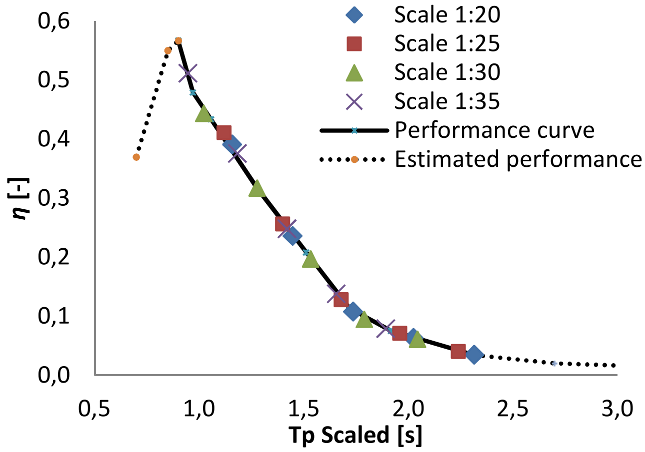

Fig. 16: η of the wave states characterizing the Danish part of the North Sea and for 4 different scaling ratios.

As the scaling ratio increases, the scaled wave period of the wave states decreases. This results mainly in an increase in corresponding η for the given wave state as they slide up the performance curve.

Based on the performance that is given in Fig. 16 and on the wave scatter diagram for Point 3 in the Danish part of the North Sea, estimations regarding the performance have been made and are presented in the following Table 3.

Table 3: Estimation of the WEPTOS performance at the Danish North Sea for 4 scaling ratios and 2 load factors.

Absolute & relative scale			**23.4***	1	**25**	1.07	**30**	1.28	**35**	1.50
Length of a leg [m]			89		111		148		185	
Rotor width & chord [m]			2.9	3.9	3.6	4.9	4.8	6.5	6.0	8.2
Combined rotor width [m]			115		144		192		240	
LF [-]			**0.33**	**0.42**	**0.33**	**0.42**	**0.33**	**0.41**	**0.32**	**0.39**
Overall η [-]			0.10	0.10	0.12	0.11	0.15	0.14	0.19	0.17
Average Pmech [kW]			379	363	452	430	721	677	1012	933
Max Pmech. [kW]			1147	860	1368	1026	2196	1647	3152	2364
AEP [GWh]			3.3*	3.1	3.9	3.7	6.2	5.9	8.8	8.1
Relative AEP to ref. [-]			1.00	0.96	1.19	1.13	1.90	1.79	2.67	2.46
Wave State	Hs	Tp	η	*Pmech*	η	*Pmech*	η	*Pmech*	η	*Pmech*
	[m]	[s]	[-]	[kW]	[-]	[kW]	[-]	[kW]	[-]	[kW]
1	1	5.4	0.39	211	0.41	237	0.44	307	0.51	413
2	1.5	6	0.24	631	0.26	733	0.32	1087	0.38	1502
3	2	6.6	0.11	782	0.13	991	0.20	1830	0.25	2691
4	2.5	7.2	0.06	947	0.07	1135	0.09	1823	0.14	3097
5	3	7.8	0.03	927	0.04	1164	0.06	2094	0.08	3155

*reference for the relative values

A 185 m long scaled reproduction of the WEPTOS prototype installed in the Danish North Sea (~16 kW/m) would produce approximately 8.1 GWh yearly with a PTO capacity of 1650 kW. This corresponds to an overall η and P_{mech} of 0.17 and 677 kW, and thereby a very high *LF* of 0.39. Note again that the *LF* is high, as for an average Danish windturbine the LF is around 0.2 – 0.25 [13].

The scale has again a significant influence on the annual energy production (*AEP*) as an increase in size of 28 % (scaling ratio of 1:30 versus 1:23.4) doubles the *AEP*.

It could be conceivable to use other scaling ratios or limit the maximum P_{mech} to other values, which would further increase the *LF*. Another possibility to increase the *AEP* could be done by prolonging the length of the legs, just by adding more rotors and while keeping their dimensions identical. In this case, the overall η would remain the same, while P_{mech} would increase with the length. This makes this device very scalable, as its geometry can be adapted in two dimensions independently, which have both a significant influence on the performance.
Fig. 18 presents the average mechanical power in the different wave states and scaling ratios, together with the wave energy contribution of every wave states is also given.

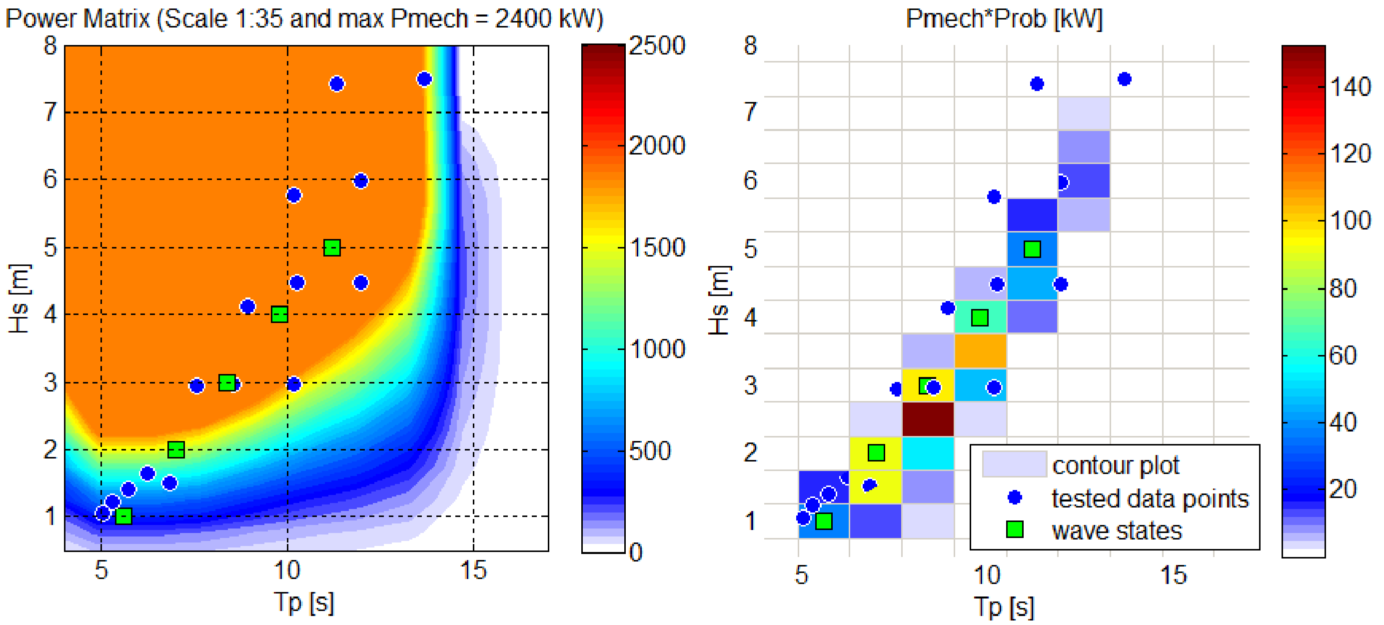

Figure 17: Power matrix and P_{mech}*Prob plot of the WEPTOS WEC at a scaling ratio of 1:35 with a maximum P_{mech} of 2400 kW and installed in Danish part of the North Sea (Point 3).

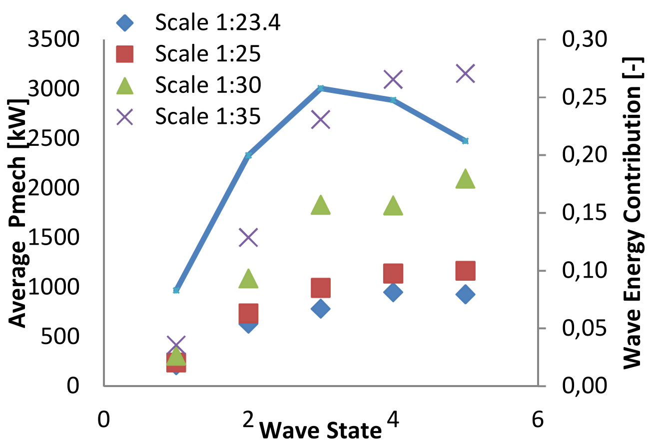

Fig. 18: Average P_{mech} for the 5 wave states representing the Danish North Sea and for 4 different scaling ratios, together with the wave energy contribution.

From Fig. 18, it can be observed that the scaling ratio has again a significant influence on P_{mech}. The scaling ratio of 1:30 appears to have more or less the same P_{mech} in WS 3 and 4 of about 1820 kW, this could be an advantage as further limiting the mechanical power in WS 5 to this number could only have a small influence on the *AEP*.

CONCLUSIONS

The WEPTOS prototype was a very realistic scale model representing a real sea power producing WEPTOS machine, making the obtained performance of the device in a wide range of wave conditions very representative. The main advantages of the device and findings of the lab tests are the following:

- The opening angle of the device enables the rotors to absorb and transfer their energy at different time intervals to the PTO system. This results in relatively smooth P_{mech}, a low generator capacity and thereby a high load factor.
- The survival mechanism, which consists of reducing the opening angle of the device to 30°, has proven to be very effective as it significantly decreases the mooring forces and reduces the structural bending moments in storm conditions to the same range as in power production wave conditions.
- The highest non-dimensional performance (η) in irregular 2D waves that has been found was 0.57 (in WS 0B). This could possibly be even higher in smaller wave conditions,

but this was not possible to be investigated due to limitations in wave generating and measuring equipment.

- The overall η and annual energy production (*AEP*) increase significantly with increasing scaling ratio, while the *AEP* could also be increased by prolonging the legs.
- At a scaling ratio of 1:15, corresponding to an overall combined rotor width of 144 m, a WEPTOS machine would produce around 0.9 GWh in front of Hanstholm harbour (P_{wave} = 6.1 kW/m). This corresponds to an average P_{mech} of 103 kW and a LF of 0. 42 with an installed PTO capacity of 250 kW.
- Similarly, in the Danish part of the North Sea (P_{wave} = 13.6 kW/m) a WEPTOS machine at a scale of 1:35, a WEPTOS machine would produce around 8.1 GWh or an equivalent average P_{mech} of 933 kW at a *LF* of 0.39 with an installed PTO capacity of 2400 kW. This means that in this case for a machine that is twice larger and which is installed at a location with a twice larger wave energy level, the *AEP* increase by 9 times. This makes this device highly scalable, which is one of the great assets of this device, besides the high performance and the small structural loads in extreme conditions relative to the loads in operation (which is not included in this paper).
- The linear PTO loading proved to be better than the constant PTO loading, but only in the medium-size wave conditions (wave state 2, 3 and 4). An optimisation of the settings of the linear PTO would probably enable it to perform as the best PTO loading in all wave conditions, which would even result in higher performances.
- Alterations to the spectral shape (peak enhancement factor of the JONSWAP spectrum) seem to have only a limited impact on the performance, as a maximum drop in performance of 10 % was found, which was for a narrower spectrum. The performance did not appear to be influenced by having a broader wave spectrum in wave state 2 and 4.
- The influence of directional spreading on the performance was also small as for an S factor of 5 (moderate/significant 3D waves) a drop in performance of 20 % was found in wave state 2 and 4, relative to the reference case (long crested irregular waves). However, it should be noted that the PTO loading was not optimised to these specific conditions (neither for the spectral shape) as the settings that were found optimal for the reference were used.

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