EXPERIMENTAL STUDY OF THE WEPTOS WAVE ENERGY CONVERTER

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ABSTRACT
This paper presents the power performance results of the experimental study of the WEPTOS wave energy converter (WEC). This novel device combines an established and efficient wave energy absorbing mechanism with an adjustable structure that can regulate the amount of incoming wave energy and reduce loads in extreme wave conditions. This A-shaped floating structure absorbs the energy in 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 the 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 mechanical power available to the power take off system of the WEPTOS WEC for two locations of interest. These are a generic offshore location in the Danish part of the North Sea (Point 3) and the location of the Danish wave energy centre (DanWEC) in front of Hanstholm harbour.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>Annual energy production</td>
<td>[GWh]</td>
</tr>
<tr>
<td>Contrib</td>
<td>Contribution to the available wave power</td>
<td>[-]</td>
</tr>
<tr>
<td>H_s</td>
<td>Significant wave height</td>
<td>[m]</td>
</tr>
<tr>
<td>H_m0</td>
<td>Estimation of the significant wave height</td>
<td>[m]</td>
</tr>
<tr>
<td>PTO</td>
<td>Power take off</td>
<td></td>
</tr>
<tr>
<td>P_mech</td>
<td>Average mechanical power</td>
<td>[kW]</td>
</tr>
<tr>
<td>Prob</td>
<td>Probability of occurrence</td>
<td>[-]</td>
</tr>
<tr>
<td>P_wave</td>
<td>Wave power level</td>
<td>[kW/m]</td>
</tr>
<tr>
<td>T_p</td>
<td>Peak wave period</td>
<td>[s]</td>
</tr>
<tr>
<td>G</td>
<td>Peak enhancement factor (JONSWAP)</td>
<td>[-]</td>
</tr>
<tr>
<td>S</td>
<td>Directional spreading factor</td>
<td>[-]</td>
</tr>
<tr>
<td>S_p</td>
<td>Wave steepness based on T_p</td>
<td>[-]</td>
</tr>
<tr>
<td>WEC</td>
<td>Wave energy converter</td>
<td></td>
</tr>
<tr>
<td>WS</td>
<td>Wave state</td>
<td></td>
</tr>
</tbody>
</table>

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 a (1:3) gearbelt connected to an PLC controlled electrical step motor. The torque was measured between the axle and the PTO system.
The opening angle between the two main legs is adaptable, as it is regulated by the position of the transversal beams on the legs (Fig. 3). This allows the device to adapt its configuration relative to the wave, with opening angles ranging from 30° to 120°. It improves its survivability, by significantly reducing the mooring forces and structural bending moments during storm conditions, and also enables to regulate the wave energy available to the device [2]. Having an opening angle towards the waves softens the power transfer to the power take off (PTO) system, as the rotors absorb and transfer their energy at different time intervals. This smoothens the rotation of the axle 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].

This paper presents the results from tank testing in a large 3-D wave basin using an advanced prototype in terms of power performance 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 at different scaling ratios and 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 highly representative scale model of 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 the tank tests in the CCOB facility in Santander, Spain [4], resulting in a large 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 has 2 legs of lengths of approximately 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 complete 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 system.

Torque measurement sensors 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 ($τ$). The two electrical step motors used to simulate the PTO system were connected through a Profibus connection to the main PLC, which regulated the PTO loading and acquired various relevant data including the rotational speed ($ω$). 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 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:

$$\eta = \frac{P_{mech\, starboard} + P_{mech\, port}}{P_{wave} \cdot 2 \cdot 20 \cdot 0.24}$$  (1)
This definition presents the non-dimensional performance independently from the opening angle, making the \( \eta \) 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:

\[
\text{Contrib}_\text{bin} = \frac{(P_{\text{wave}})_{\text{bin}} \cdot \text{Prob}_\text{bin}}{\sum_{\text{bin}=1}^{n} ((P_{\text{wave}})_{\text{bin}} \cdot \text{Prob}_\text{bin})}
\]  

(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. \( H_{\text{ref}} \) and \( T_{p} \)) and the physical dimensions of the device can be scaled following Froude’s scaling law [6].

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

\[
\eta_{\text{overall}} = \sum_{i=1}^{n} \eta_{i} \cdot \text{Contrib}_{i}
\]

(3)

The mechanical power output (\( P_{\text{mech}} \)) for a certain wave condition corresponds to multiplying the average available wave power (using the deep water approximation, \( P_{\text{wave}}=0.49T_{p}H_{\text{ref}}^{2} \) and \( T_{p} = T_{p}/1.15 \)) to the \( \eta \) of the device in those wave conditions.

\[
P_{\text{mech}_{i}} = P_{\text{wave}_{i}} \cdot \eta_{i}
\]

(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.

\[
P_{\text{average}} = \sum_{i=1}^{n} P_{\text{mech}_{i}} \cdot \text{Prob}_{i}
\]

(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].

\[
\text{AEP} = P_{\text{average}} \cdot 8760
\]

(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.

\[
LF = \frac{P_{\text{average}}}{\text{maximum} (P_{\text{mech}})}
\]

(7)

**Tested wave conditions**

The main aim of the experimental tests was to assess the power performance of the device, the mooring forces and structural bending moments, however 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) 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) at a scaling ratio of 1:23.4 [9][10]. 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.

**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. Four different wave spreading factors (\( S \)) were used (99, 10, 5 and 2), where 99 is the reference and 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.

**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 only some of the wave states, due to time limitations. The constant PTO loading consisted of having a fixed target torque value on the axle throughout the whole test, which can be seen in Fig. 4. The measured torque (\( \tau \)) resulted relatively scattered, but still around the target value.
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.

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. The first line presents the scaling ratio of the WEPTOS device relative to the WEPTOS prototype (absolute) and relative to the smallest absolute scaling ratio for that location (relative). This is followed by the scaled dimensions of the leg and rotors. 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 Pmech is given for each wave state.

RESULTS & DISCUSSION

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.

Wave height and period dependency

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

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

### Non-dimensional performance of the WEPTOS prototype

The highest $\eta$ that has been obtained, after optimization of the PTO loading, 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 $\eta$ of the WEPTOS prototype in the production wave states, with linear and constant PTO loading.**

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

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 $\eta$ of WEPTOS machine in the wave conditions of locations of interest, by scaling the corresponding wave conditions down.

**Fig. 8: Presentation of $\eta$ with a constant and linear PTO loading, together with the performance curve.**

In general, the $\eta$ 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 $\omega$, making the resulting PTO loading being suboptimal. In WS 5, large scatter was encountered in the $\omega$-$\tau$ 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 $\eta$ could possibly still be found at a lower $T_p$, but these wave conditions could not be realized in the lab, therefore a (conservative) decreasing curve is used.

A two dimensional performance curve ($\eta, T_p$) 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 $\eta$ 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 states 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 \(\eta\). The reference values of \(G\) and \(S\) are 3.3 and 99 and the values corresponding to the alterations are mentioned in the name.

In general the influence of the spectral shape and directional spreading appears to be very low in small wave conditions. For a broader spectrum (\(G1\)), 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 negligible in the smaller 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.

The \(\eta\) 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.

As the scaling ratio increases, the scaled wave period of the wave states decreases. This results mainly in an increase in corresponding \(\eta\) 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 Table 2.
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 \( P_{\text{mech}} \). Note that the LF of an average Danish wind turbine is around 0.2 – 0.25 [12].

The \( \eta \) and AEP increases significantly with the scaling ratio, as they increase six-fold 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. The impact of limiting the maximum \( P_{\text{mech}} \) 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 \( P_{\text{mech}} \) and indirectly \( \eta \) for different scaling ratios and wave states are presented in Fig. 14.

![Figure 13: Power matrix and \( P_{\text{mech}} \) * Prob plot of the WEPTOS WEC in Hanstholm at a scaling ratio of 1:15 with a maximum \( P_{\text{mech}} \) of 250 kW, with scaled tested wave conditions (blue dots) and corresponding wave states to Hanstholm (green squares).](image)

![Figure 14: Average \( P_{\text{mech}} \) of the WEPTOS for the 5 WS of Hanstholm harbour and for 4 scaling ratios.](image)
Danish part of the North Sea

The generic location in the Danish part of the North Sea (Point 3), for which the AEP of most Danish developing WEC is 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 [13]. 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 \( T_p \).

As the scaling ratio increases, the scaled wave period of the wave states decreases. This results mainly in an increase in corresponding \( \eta \) 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.

<table>
<thead>
<tr>
<th>Absolute &amp; relative scale</th>
<th>23.4*</th>
<th>1</th>
<th>25</th>
<th>1.07</th>
<th>30</th>
<th>1.28</th>
<th>35</th>
<th>1.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of a leg [m]</td>
<td>89</td>
<td>111</td>
<td>148</td>
<td>185</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor width &amp; chord [m]</td>
<td>2.9</td>
<td>3.9</td>
<td>3.6</td>
<td>4.9</td>
<td>4.8</td>
<td>6.5</td>
<td>6.0</td>
<td>8.2</td>
</tr>
<tr>
<td>Combined rotor width [m]</td>
<td>115</td>
<td>144</td>
<td>192</td>
<td>240</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF [-]</td>
<td>0.33</td>
<td>0.42</td>
<td>0.33</td>
<td>0.42</td>
<td>0.33</td>
<td>0.41</td>
<td>0.32</td>
<td>0.39</td>
</tr>
<tr>
<td>Overall ( \eta ) [-]</td>
<td>0.10</td>
<td>0.10</td>
<td>0.12</td>
<td>0.11</td>
<td>0.15</td>
<td>0.14</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>Average Pmech [kW]</td>
<td>379</td>
<td>363</td>
<td>452</td>
<td>430</td>
<td>721</td>
<td>677</td>
<td>1012</td>
<td>933</td>
</tr>
<tr>
<td>Max Pmech. [kW]</td>
<td>1147</td>
<td>860</td>
<td>1368</td>
<td>1026</td>
<td>2196</td>
<td>1647</td>
<td>3152</td>
<td>2364</td>
</tr>
<tr>
<td>AEP [GWh]</td>
<td>3.3*</td>
<td>3.1</td>
<td>3.9</td>
<td>3.7</td>
<td>6.2</td>
<td>5.9</td>
<td>8.8</td>
<td>8.1</td>
</tr>
<tr>
<td>Relative AEP to ref. [-]</td>
<td>1.00</td>
<td>0.96</td>
<td>1.19</td>
<td>1.13</td>
<td>1.90</td>
<td>1.79</td>
<td>2.67</td>
<td>2.46</td>
</tr>
</tbody>
</table>

*reference for the relative values                      - relative values are in italic

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

Fig. 16 presents the \( \eta \) 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.

A 148 m long and scaled (1:30) reproduction of the WEPTOS prototype installed in the Danish North Sea (~16 kW/m) would produce approximately 5.9 GWh yearly with a PTO capacity of 1650 kW. This corresponds to an overall \( \eta \) and \( P_{mech} \) of 0.14 and 677 kW, and thereby a high LF of 0.41. Note again that the LF is high, as for an average Danish wind turbine the LF is around 0.2 – 0.25 [12].

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.

Besides the scaling ratios the AEP could also be increased in the same wave conditions by prolonging the length of the legs. This would correspond to adding more rotors to the legs, while keeping their dimensions identical. In this case, the overall \( \eta \) would remain the same, while \( P_{mech} \) would increase with the combined with of all the rotors. This makes this device very scalable, as its geometry can be adapted in two dimensions independently, which have both a significant influence on the AEP.

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.
CONCLUSIONS

The WEPTOS prototype was a very representative scale model of 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 efficient wave absorbing rotors to transfer their energy at different time intervals to the PTO system. This results in relatively smooth $P_{\text{mech}}$, a low generator capacity, as high $P_{\text{mech}}$ peaks are avoided, 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 [2].
- The highest non-dimensional performance ($\eta$) 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 $\eta$ and annual energy production ($AEP$) increase significantly with increasing scaling ratio (size of the rotors), while the $AEP$ could also be increased by just adding more rotors to the legs, which is a very strong asset of this device.
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 Hansholm harbour \( (P_{\text{wave}} = 6.1 \text{ kW/m}) \). This corresponds to an average \( P_{\text{mech}} \) of 103 kW and a \( L/F \) of 0.42 with an installed PTO capacity of 250 kW.

Similarly, in the Danish part of the North Sea \( (P_{\text{wave}} = 16.3 \text{ kW/m}) \) a WEPTOS machine at a scale of 1:35, a WEPTOS machine would produce around 8.1 GWh or an equivalent average \( P_{\text{mech}} \) of 933 kW at a \( L/F \) of 0.39 with an installed PTO capacity of 2400 kW. This means that in this case for a machine that is 2.3 times larger and which is installed at a location with a 2.7 larger wave energy level, the AEP increase by 9 times.

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 in the larger wave conditions. 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 found to be neglectable in the smaller wave conditions and about 20% in the larger wave conditions. 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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