

Recent Developments of Wave Energy Utilization in Denmark

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Keywords: Wave energy converters, Wave Dragon, SSG, Wave Star, Real sea testing, Wave overtopping, Low head turbines.

Abstract. This paper aims at giving an overview of the developments researchers at the Department of Civil Engineering, Aalborg University, Denmark (DCE), have been involved in within the field of wave energy utilization in Denmark over the past decade. At first a general introduction is given followed by a more thorough description of three ongoing projects. These are Wave Dragon, Wave Star and Seawave Slot-cone Generator. Common for these projects are that they are being, or will soon be, tested in real sea and have benefited from the Danish Wave Energy Program. The work by the department on these projects involves substantial laboratory testing, numerical simulations and real sea prototype testing.

Introduction

Development of technical devices to utilize wave energy for electricity production (wave energy converters, WEC's) has been going on in Denmark for the past 25 years. However, up until the establishment of the Danish Wave Energy Program (DWEP) in 1997 [1], only one device (a point absorber developed by the company Danish Wave Power) was thoroughly investigated. The DWEP, together with a simultaneously established Wave Energy Association (WEA), initiated an accelerated development and testing of numerous WEC's. The DWEP had the objective to investigate future optimal wave energy solutions by a broad development of different WEC's. Ultimately, the aim was to develop expertise and technologies enabling installation of MW to GW size wave energy plants.

The DWEP was running for a total of 4 years (from 1998 to 2002) with a total budget of 40 mill. DKR (€5.4 mill.). It was administrated by an advisory panel of experts representing hydraulic and maritime institutes in Denmark, the Folkecenter for Renewable Energy, the WEA, the Technical University of Denmark and Aalborg University. DWEP was funding the development through different stages, going from simple experiments and visualization, through intermediate phases involving further R&D and ending at prototype testing in real sea conditions. As many as 40-50 projects has been through the initial phase with simple testing of new ideas, while roughly 10 projects have been through the phase of further R&D. Approx. half of these projects have been tested at DCE. Only one concept was supported by DWEP at the level of real sea prototype testing, namely the slack moored floating overtopping based WEC Wave Dragon (WD). This project received approx. 10 mill. DKR (€1,3 mill.) for building a scale 1:4.5 prototype of a North Sea power plant (4 MW installed capacity), for deployment in the inner waters of Nissum Bredning in the north western part of Denmark. This grant was the last given before the DWEP was closed down in 2002.

Among the outcomes of the DWEP are also a mapping of the wave energy resource in the Danish region [2] and procedure for evaluation of WEC's [3].

In the following a more thorough presentation of the WD project is given, followed by presentations of two other concepts, namely Wave Star (WS) and Seawave Slot-cone Generator (SSG), which are building on top of R&D carried out during the DWEP, and is now undergoing, or planning, real sea prototype testing. Common for these three projects is that the DCE is, and have been, heavily involved in the associated R&D. DCE is also as EU founded partner involved in the instrumentation, monitoring and evaluation of the real sea performance of the devices.



Fig. 1: The Wave Dragon Nissum Bredning Prototype in action.

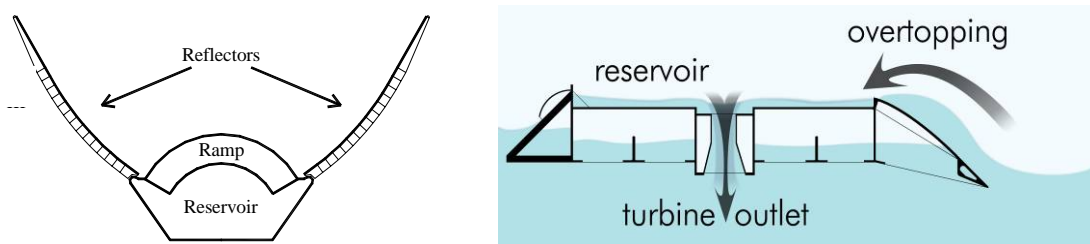


Fig. 2: Main components of WD (left) and basic working principle (right).

Wave Dragon

The WD is a floating offshore wave energy converter of the overtopping type being developed by the company Wave Dragon ApS (www.wavedragon.net). A full scale WD designed for an appropriate climate would have an installed power of 4-11 MW. A prototype scaled at 1:4.5 of a North Sea 4 MW production plant and rated at 20 kW has been tested in Nissum Bredning, a large inland waterway in Denmark (average available wave energy approx. 0.4 kW/m), since March 2003, see fig. 1.

The concept works by waves overtopping a ramp, filling a floating reservoir with water at a higher level than the mean sea level. This head of water is used for power production through the specially designed hydro turbines, see fig. 2.

The prototype has all the features of an operational power plant, including: slender wave reflectors to focus the energy of the waves towards the ramp, a pneumatic system to adjust the floating level of the platform; seven Propeller turbines mounted with permanent magnet (PM) generators to convert the potential energy of the water; and an inverter system to control the variable speed of the turbines. Furthermore, three calibrated dummy turbines are used to process overtopping flow rates that exceed the capacity of the Propeller turbines. The power generated is exported to the Danish national grid via a three phase sub-sea power cable.

WD uses the energy in the water directly via water turbines, i.e. a one-step conversion system, which yields a very simple construction and has only one kind of moving parts; the turbines. But yet WD represents a very complex design, where intensive efforts by universities and industry have been spent on designing, modelling and testing in order to:

- Optimize overtopping.
- Refine hydraulic response: anti-pitching and anti-rolling, buoyancy etc.
- Reduce (the effect of) forces on wave reflectors, mooring system etc.
- Develop efficient turbines for extremely low and varying head.
- Develop a turbine strategy to optimise power production.
- Reduce construction, maintenance and running costs.

All of this has been done with one goal: to produce as much electricity as possible at the lowest possible costs - and in an environmental friendly and reliable way.

Up to now, €3 mill. have been spent on the development of the WD. Half of this has been funded by the participating partners and sponsors, the rest from public and other funds (primarily from the Danish Energy Authority and the European Commission). The budget for the 1:4.5 prototype phase was approximately €3.3 mill.

WD has been subject to thorough testing in model scale carried out in wave tanks at Aalborg University and University College Cork. These tests have been focused on both performance optimization in terms of power production, and on survivability. The design of the ramp profile have been based on the findings of a Ph. D. study on overtopping of marine structures, where focus was put on parameter ranges relevant for overtopping based WEC's [4]

WD and other similar overtopping based WEC's have no endstop problems as it is the case for numerous other kinds of WEC's, as the power take-off system – the turbines – is not loaded significantly harder in extreme conditions than in operational conditions. The largest waves simply overrun the structure and the WD does not rely on active systems to survive. The structure is designed to withstand a wave condition with a 100 years return period.

Furthermore, a highly efficient power take-off in the form of an axial turbine in scale 1:3.5 has been developed. The turbine has been tested in the acknowledged turbine test stand at Technical University Munich. A significant development and design optimisation program has been carried out in a fruitful cooperation among a number of European companies [5].

A power simulation software tool for the WD has also been made based on the above mentioned studies, in order to simulate and evaluate the influence various parameters such as reservoir sizes, turbine characteristics and control strategy, on the overall power production of the device [6].

The prototype testing of the WD in Nissum Bredning has resulted in detailed information on the performance of the device in terms of overtopping rates and power production. An enormous quantity of data has been collected during the testing period, which has not all yet been fully analysed. However, the work done so far has confirmed that the performance predicted on the basis of wave tank testing and turbine model tests can be achieved in a full scale prototype, see eg. [7].

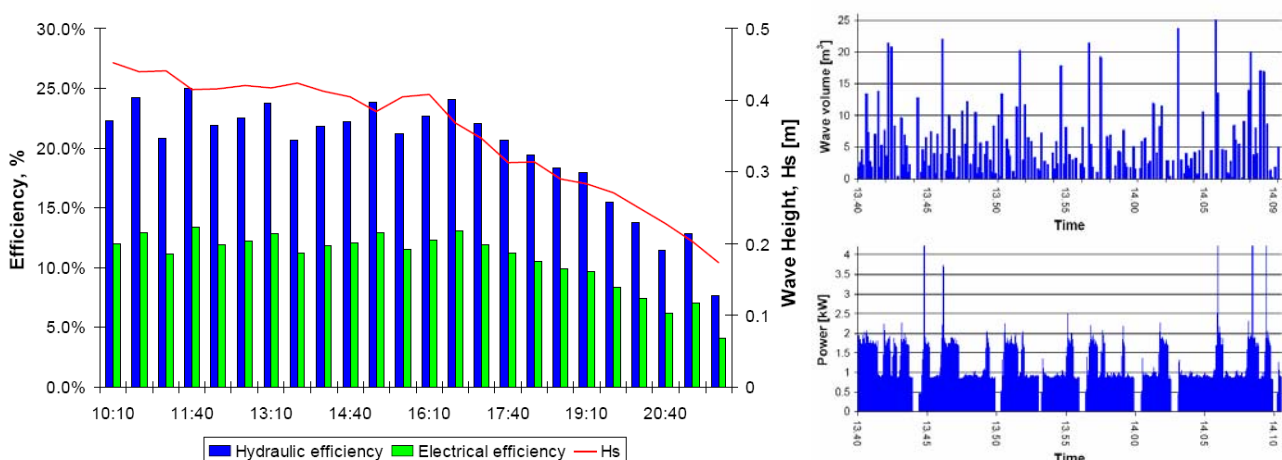


Fig. 3: Example of hydraulic efficiency of the Wave Dragon Prototype over half a day (left) at relatively low floating level. Wave by wave overtopping volumes measured over a 20 min. interval (same day as showed on left side) (right, upper). Corresponding power production data is given below (right, lower) [8].

The performance of WD is illustrated by sample data in fig. 3. It should be noted that the efficiency of the power conversion system (from water in reservoir to electricity to the grid is (depending of the head) is only approx. 50 % due to the low power levels and cannot be scaled up directly due to a number of friction losses. Efficiency will in full scale be approx. 85%. The two graphs to the right in fig. 3 illustrate the irregular overtopping and the smoothening effect of the reservoir. The shown sample data is from a situation where the reflectors were not mounted on the prototype.

Lots of invaluable experiences regarding performance of control strategies, materials, mooring system, ecological impact etc. has been achieved. So far the real sea testing of the WD prototype has proven its seaworthiness, floating stability and power production potential. Operation of the device in the harsh offshore environment has led to a number of component failures. These have been investigated, and technical solutions have been found.

Wave Dragon ApS are presently developing a demonstration plant off the south western coast of Wales (UK). This demonstration plant will have a total width between the reflectors of 300 m, a total weight of 33,000t (structure in concrete) and have an installed capacity of 7 MW. The EU founded R&D project related to this plant has been initiated this autumn (2006).

Wave Star

The WS is a so-called multi point absorber being developed by the company Wave Star Energy (www.wavestarenergy.dk). The machine is equipped with a number of floats which are moved by the waves to activate pumps, which press oil into a common transmission system, the pressure of which drives a hydraulic motor. The motor, in turn, drives the generator of the WEC. In the event of a storm the floats are lifted to a safe position – on the large-scale machine they will hang 20 meters above the surface, see fig. 4. A sensor on the seabed ahead of the machine measures the waves and ensures that the storm security system is automatically activated. The system can also be remotely operated.

After intensive performance and loading testing in the wave tank [9] and numerical simulations [10] a 1:10 model has been constructed and is currently being tested in Nissum Bredning [11], see fig. 4. This prototype is equipped with 40 hemisphere shaped floats, each with a diameter of one meter. The model has a 5.5 kilowatt generator. The full scale production device will be equipped with floats of 10 meters in diameter and a three megawatt generator.

The WS generates electricity even from very small waves. For the 1:10 model, waves only need to be 0.10 m high. Calculations and tests show that the machine produces energy around 90 percent of the time, and that it will run on maximum power 30 percent of the time. When appropriately scaled to the dominating wave climate, the power of a WEC becomes around 11 times greater, each time the machine doubles in size.

The plan for the near future development of the WS includes also a scale 1:2 production test unit with only two floats. These are expected to be installed at the harbor of Hanstholm during next year (2007). This is done as a part of the preparation of installation of a 500 kW machine which is currently under development. The commercialization of the WS will begin as soon as this machine has produced satisfactory results in the North Sea. According to the plan this should be in the course of the next three to four years.

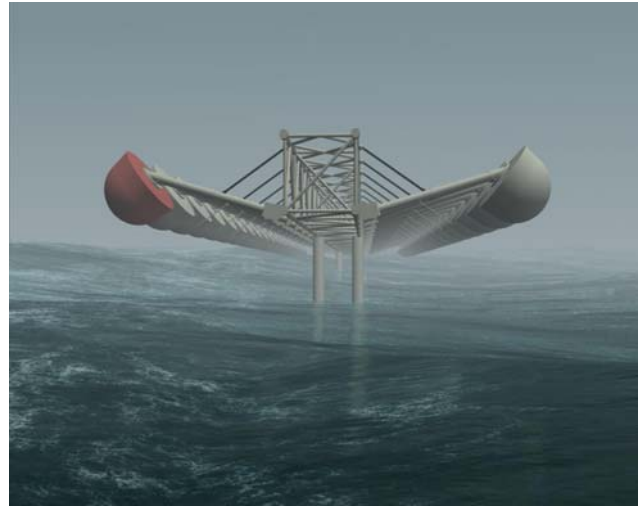
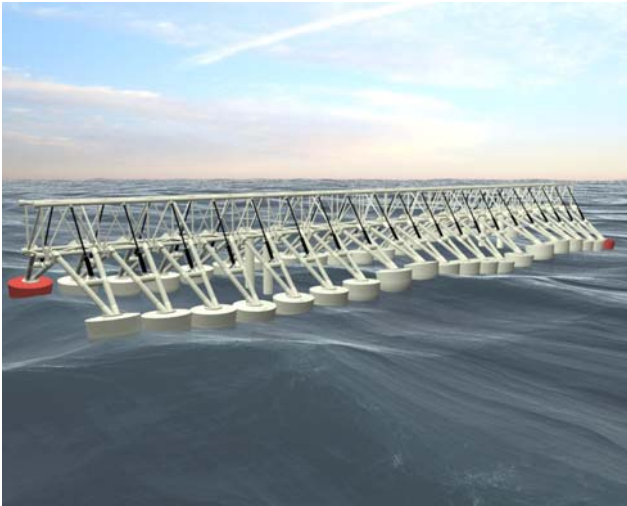


Fig. 4: Illustration of Wave Star in normal operation mode (left) and in storm safe mode (right).



Fig. 5: The Wave Star Nissum Bredning 1:10 scale prototype (upper). Wave Star model in wave tank (left), and prototype in storm safe mode (right).



Fig. 6: Illustration of the Seawave Slot-cone as an integrated part of a breakwater (left).
Photo montage of pilot plant to be installed on the west coast
at the island of Kvitsøy, near Stavanger, Norway (right).



Fig. 7: Performance optimization of geometric layout through wave tank model tests (left).
3D performance model testing in wave tank with model (right).

Seawave Slot-cone Generator

The Seawave Slot-cone Generator (SSG), under development by the Norwegian company WaveEnergy AS (www.waveenergy.no), is an overtopping based WEC utilizing a total of three reservoirs placed on top of each other. The SSG is designed as a near shore concrete structure (suitable for integration in eg. a breakwater) with the turbine shaft and the gates controlling the water flow as virtually the only moving part of the mechanical system, see figure 6. A prototype plant with a width of 10 m is planned for deployment at the west coast of Kvitsøy, Norway (near Stavanger) during 2007. At this site the average available wave energy resource is approx. 18 kW/m.

In the design of such structures the overtopping prediction formulae available in the literature are not sufficient, as these are typically only valid for single reservoir layouts and hold no information of the vertical distribution of the overtopping above the lowest reservoir crest. Furthermore, the geometry of the fronts on the individual reservoirs above the lowest one also influences the overtopping rates into the individual reservoirs.

On this background physical model studies have been performed (see figure 7) in which it was investigated how a range of different geometrical parameters influence the overtopping rates for the individual reservoirs when the structure is subjected to heavily varying wave conditions [12]. The results have been evaluated and used for the formulation of expressions for describing the vertical distribution of overtopping, which then can be used for calculation of overtopping rates into multi level reservoirs. This work has been used to optimize the crest levels and geometrical layout of the SSG structure in a combination of irregular wave conditions, focusing on maximizing the overall obtained potential energy in the overtopping water. An overall hydraulic efficiency (ratio between wave energy contents in waves and potential energy in overtopping water at crest level, averaged

over the prevailing wave conditions, with corresponding probabilities) of more than 50 % has been achieved.

Based on the obtained overtopping expressions and turbine characteristics, a power simulation software tool has been developed [13]. This tool has been used for evaluation and optimization of a SSG structure in varying sea conditions, geometrical setup, control strategies, turbine characteristics etc. Simulations have shown that for the chosen geometry of the pilot plant, with its limited sizes of reservoirs and an installed generator capacity of approx. 150 kW, the overall average wave to wire efficiency becomes approx. 20 %.

As a part of the specific design of the Kvitsøy pilot plant 3D wave tank model tests have been performed to establish the wave loadings on the structure in extreme conditions [14]. These tests showed that the loadings on structure generally was of a pulsating nature, with a magnitude comparable to those predicted by Tanimoto & Kimura [15] for sloping sea walls. An exception from this was found to be the rear vertical wall in the upper reservoir, where the loadings were dominated by damped impacting water jets resulting in considerably larger, short duration, peaks. This led to the conclusion that such a vertical wall should be avoided in the final design.

Model tests on hydraulic performance of the pilot plant subjected 3D and oblique wave attack is currently ongoing, see fig. 7, right. These tests are performed to establish overtopping data which can be used for comparison with the prototype data, once these begins to arrive from the pilot plant.

In addition to the planning and construction of the pilot plant at Kvitsøy, various other project development options are being investigated by WaveEnergy AS.

Conclusion

An overview of the recent developments within the field of wave energy utilization in Denmark has been given, exemplified by three different projects in which the Department of Civil Engineering at Aalborg University, Denmark, have been heavily involved. The current state is that real sea testing of prototypes at reduced sizes are ongoing, results are generally confirming findings from laboratory model testing, numerable practical problems have been met, but none of them are considered to be show stoppers, i.e. these problems are all solvable through proper engineering, and demonstration plants are under preparation. It is expected that within the coming 3-5 years full size demonstration plants of the described types will be in the oceans, going towards commercialization.

References

- [1] Nielsen, K and Meyer, N. I.: *The Danish Wave Energy Programme*. 3rd European Wave Energy Conference, Patras, Greece, 30 September – 2 October, 1998.
- [2] *Kortlægning af bølgeenergiforhold i den danske del af Nordsøen*. ENERGISTYRELSEN, J.no. 51191/97-0014, Juni 1999. (Title in English: Mapping of wave energy resource in the Danish part of the North Sea.)
- [3] *Bølgekraft – forslag til forsøg og rapportering. Forslag til systematik i forbindelse med afprøvning af bølgekraftanlæg*. Bølgekraftudvalgets Sekretariat (DHI, AAU, DMI, RAMBØLL), Januar 1999. In Danish. (Title in English: Wave power – proposal for tests and reporting.)
- [4] Kofoed J. P.: *Wave Overtopping of Marine Structures – Utilization of Wave Energy*. Ph. D. Thesis, defended January 17, 2003 at Aalborg University. Hydraulics & Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, ISSN 0909-4296, Series Paper No. 24, December, 2002.
- [4] Kofoed, J. P., Frigaard, P., Friis-Madsen, E. and Sørensen, H. C.: *Prototype testing of the wave energy converter Wave Dragon*. Renewable Energy Journal, 31 (2006), pp. 181 - 189.

- [5] Kofoed, J. P. and Frigaard, P.: *Hydraulic Response of the Wave Energy Converter Wave Dragon in Nissum Bredning*. Hydraulics and Coastal Engineering No. 11, ISSN: 1603-9874, Dep. of Civil Eng., Aalborg University, December 2004.
- [6] Jakobsen, K. P. and Frigaard, P.: *User's manual for the program Wave Dragon power simulation*. Technical report, CRAFT program Low-Pressure Turbine and Control Equipment for Wave Energy Converters, Wave Dragon, Hydraulics & Coastal Engineering Laboratory, Aalborg University, 1999.
- [7] Tedd, J., Kofoed, J.P., Knapp, W., Friis-Madsen, E., and Sørensen, H.C.: *Wave Dragon, prototype wave power production*. World Renewable Energy Congress - IX, Florence, Italy, August, 19-25th, 2006.
- [8] Sørensen, H. C., Tedd, Friis-Madsen, E. and Friis-Madsen, E.: *Preliminary Results from Second Phase Sea Testing of the Wave Dragon Prototype Wave Energy Converter*. International Conference Ocean Energy, Bremerhaven, Germany, Oct. 23-24th, 2006.
- [9] Kramer, M. and Andersen, T. L.: *Wave Star – Skala 1:40 modelforsøg, forsøgsrapport 2*. Hydraulics and Coastal Engineering No. 14. ISSN: 1603-9874. Aalborg University, Department of Civil Engineering. 2005. In Danish. (Title in English: Wave Star – Scale 1:40 model tests, test report 2)
- [10] Kramer, M., Brorsen, M. and Frigaard, P.: *Wave Star – Hydrodynamisk interaktion mellem 5 flydere*. Hydraulics and Coastal Engineering No. 7. ISSN: 1603-9874. Aalborg University, Department of Civil Engineering. 2004. In Danish. (Title in English: Wave Star – Hydrodynamic interaction between 5 floats.)
- [11] Steenstrup, P. R.: *Wave Star Energy – new wave energy converter, which is now under going sea trial in Denmark*. International Conference Ocean Energy, October, 23-24th, 2006, Bremerhaven, Germany.
- [12] Kofoed, J. P.: *Vertical Distribution of Wave Overtopping for Design of Multi Level Overtopping Based Wave Energy Converters*. Paper presented an to be published in proceedings of the 30th International Conference on Coastal Engineering (ICCE 2006), San Diego, USA, 4th – 8th Sept., 2006.
- [13] Meinert, P., Gilling, L., and Kofoed, J. P.: *User manual for SSG Power simulation 2*. Hydraulics and Coastal Engineering No. 44, ISSN: 1603-9874, Dep. of Civil Eng., Aalborg University, June 2006.
- [14] Kofoed, J. P., Vicinanza, D. and Osaland, E.: *Estimation of Design Wave Loads on the SSG WEC Pilot Plant based on 3-D Model Tests*. ISOPE 2006, San Francisco, USA, May 28th - June 2nd, 2006.
- [15] Tanimoto, K., and Kimura, K.: *A Hydraulic Experimental Study on Trapezoidal Caisson Breakwaters*. Technical Note No. 528, Port and Harbour Research Institute, Yokosuka, Japan. 1985. (in Japanese)