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Prototype Testing of the Wave Energy Converter Wave Dragon

by

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ABSTRACT

The Wave Dragon is an offshore wave energy converter of the overtopping type. It consists of two wave reflectors focusing the incoming waves towards a ramp, a reservoir for collecting the overtopping water and a number of hydro turbines for converting the pressure head into power.

In the period from 1998 to 2001 extensive wave tank testing on a scale model was carried at Aalborg University. Then, a 57 x 27 m wide and 237 tonnes heavy (incl. ballast) prototype of the Wave Dragon, placed in Nissum Bredning, Denmark, was grid connected in May 2003 as the world's first offshore wave energy converter.

The prototype is fully equipped with hydro turbines and automatic control systems, and is instrumented in order to monitor power production, wave climate, forces in mooring lines, stresses in the structure and movements of the Wave Dragon. During the last months, extensive testing has started.

In the coming 1½ years an extensive measuring program will establish the background for optimal design of the structure and regulation of the power take off system. Planning for deployment of a 7 MW power production unit in the Atlantic within the next 2-3 years is in progress.

INTRODUCTION

Wave Dragon (WD) is an offshore wave energy converter of the overtopping type where each unit will have a rated power of 4-10 MW depending on how energetic the wave climate is at the deployment site. As part of the development activities towards a full size production plant in 2006 a grid connected prototype of the WD is presently being tested in a Danish fjord (a scale 1:4.5 of a North Sea production plant).

WD consists of three main elements:

- Two patented wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially and thereby increasing energy capture by 70 % in typical wave conditions.
- The main structure consisting of a patented doubly curved ramp and a water storage reservoir.
- A set of low head propeller turbines for converting the hydraulic head in the reservoir into electricity.

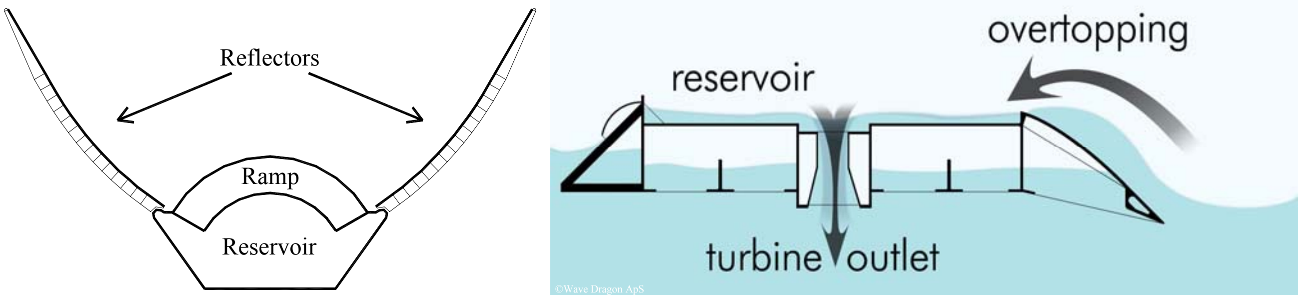

Figure 1. Left: Main components of the Wave Dragon. Right: The basic principle of the Wave Dragon, 1) waves overtopping a ramp, 2) water stored in a reservoir above sea level and 3) water discharged through hydro turbines. Wave Dragon floats on open air-chambers used to adjust floating level.

Figure 2. Wave Dragon prototype at test site.

When waves have been focused by the reflectors they overtop the ramp and fill the reservoir, which is situated at a higher level than the surrounding sea. This hydraulic head is utilized for power production through the hydro turbines.

WD is unique among wave energy converters as it 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. This is essential for any device operating offshore where maintenance is difficult to perform and where the extreme forces, fouling etc. seriously affect any moving parts.

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.

The potential world-wide wave energy contribution to the production of energy is estimated between 10 and 50 % of the world electricity consumption, Pontes & Falcao, 2001. The wave energy resources are illustrated in figure 3 showing the energy density in kW per meter wave front along different coasts around the world.

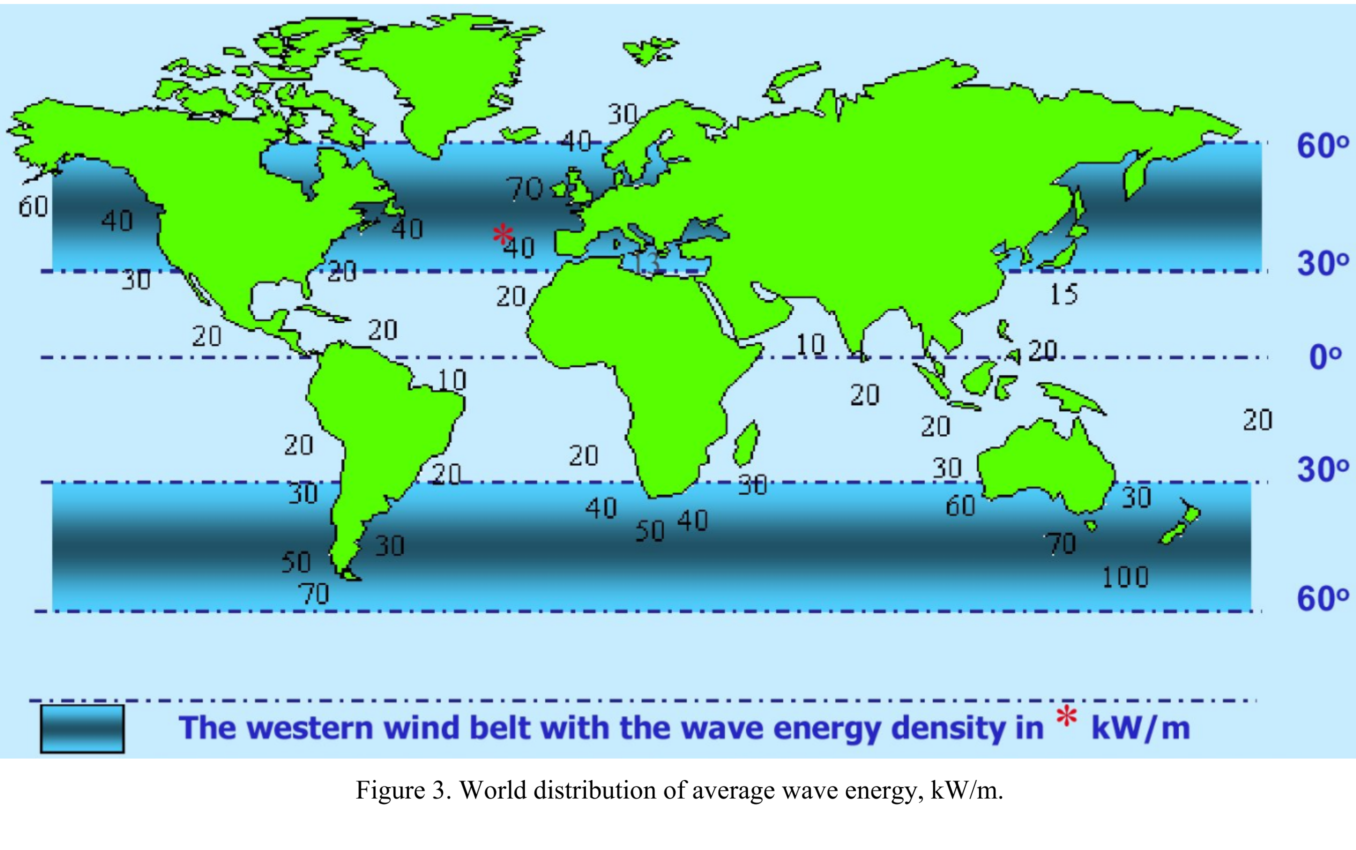

Figure 3. World distribution of average wave energy, kW/m.

HISTORY OF DEVELOPMENT

The development of the project was initiated in the late 1980's by the inventor M.Sc. Erik Friis-Madsen. Since then, the work on the project has involved a wide variety of universities and industrial partners. An overview of the overall development is given in Table 1.

Phase 1 1987-1996	Formulation of the idea/concept, energy and economic considerations, patent application. Financial support from EU to establishment of international co-operation. Two B.Sc. thesis, Copenhagen University College of Engineering, Denmark.
Phase 2 1997	Testing of a simple model scale 1:45 in a wave tank to establish basic data on reflectors, ramp and energy efficiency. M.Sc. thesis, Aalborg University, Denmark.
1997-1998	Establishment of an EU Joule Craft project (phase 3a) and Research Feasibility Study.
Phase 2a 1998	Building of a floating model (scale 1:50) at Danish Maritime Institute. Testing in a wave tank at Aalborg University to establish the response from waves of different height, the magnitude of the forces in the mooring system and the energy efficiency.
Phase 2b 1999	Adjustment of the model and the design parameters with reference to phase 3
Phase 3a 1998-2000 1998-1999	Further testing of a model scale 1:50 to establish the design parameters of important parts (flow in the turbines, strategy for choice of turbines). Optimising of the power unit (turbines, cable connections, transformation, generators). Optimisation of turbines and reservoir. B.Sc. thesis, Copenhagen University College of Engineering. M.Sc. thesis Aalborg University.
Phase 3b 2000	Development and tests of an axial turbine with variable speed and 2 different inlet types and 2 different runner-wheels.
Phase 3c 2000-2001	Sequential modifications and testing of the existing 1. generation scale 1:50 model. The test shows the influence on WD's performance by changes in different geometry and mass distribution parameters. The test series established improved 2. generation design for a scale 1:4.5 prototype. Ph.D. thesis at Aalborg University on ramp design.
Phase 4 2002-2005	Design and deployment of a scale 1:4.5 prototype in a Danish inlet (Nissum Bredning) with wave conditions resembling a downscaled North Sea climate.
Phase 5 2003-2006	Planning of a full size production plant for deployment the North Sea or the Atlantic.

Table 1. History of the WD development.

The WD development costs to date amounts up to 8 mill. €. 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 Commision). The budget for phase 4 is approximately 3.3 mill. €.

WD has been subject to thorough testing in scale 1:50 carried out in wave tanks at Aalborg University and University College Cork, and 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. Furthermore, a significant development and design optimisation program has been carried out in a fruitful cooperation among a number of European companies.

THE STRUCTURE

WD is moored (like a ship) in relatively deep water, i.e. more than 25 m and preferably +40 m to take advantage of the ocean waves before they loose energy as they reach the coastal area. This is in contrast to many known wave energy converters that are either built into the shoreline or fixed on the seabed in shallow water.

WD is constructed with open air-chambers where a pressurized air system makes the floating height adjustable. Thus, the crest freeboard can be adjusted to yield the maximum overtopping efficiency in different wave conditions. Furthermore, the open air-chambers reduce the movements of the main body, as the wave induced pressure on the underside of the structure compresses air rather than moving the body.

WD is designed to be constructed in a combination of reinforced concrete and steel. A full size unit for a 24 kW/m wave climate will have a weight of 22,000 tonnes including ballast and a width of 260 meters between the tips of the wave reflectors. The reservoir capacity will be 5,000 m3.

Figure 4. Left: WD prototype at launch in March 2003. The open air-chambers are used to control the floating level. Right: WD prototype in heavy wave conditions.

The prototype deployed in Nissum Bredning is a steel plate construction which has a steel weight of 150 tonnes and a total weight of 237 tonnes including ballast. A steel construction has been chosen for the prototype in order to ease the measurement of stresses and as the lifetime for the prototype is limited to a few years.

The size of the WD depends on the wave climate. In Table 2 dimensions of the WD are given for different average wave energy densities.

Average wave energy density, kW/m	Prototype (0.4)	24	36	48	60
Width, m	57	260	300	390	390
Weight incl. ballast, tons	237	22,000	33,000	54,000	54,000
Reservoir capacity, m^3	55	5,000	8,000	14,000	14,000
Number of turbines	1+3+6	16	16-20	16-20	16-24
Annual power production, GWh/y	-	12	20	35	43
Generators (PMG), rated power, kW	2.5	250	350-450	460-700	625-940

Table 2. Dimension of WD prototype and WD's for different wave climates.

HYDRAULIC PERFORMANCE

The hydraulic performance of the WD has been optimized through numerical modelling and the use of small scale models tested in wave tanks. The optimisations includes overall structural geometry, focusing especially on reflector design and the cross section of the ramp, and has almost doubled the energy capture compared to the 1. generation design. This has lead to overtopping expression (Eq. 1) by Hald & Frigaard, 2001 based on 1:50 scale model tests. As indicated in Figure 5 the measured prototype data compares well with the expression based on laboratory tests.

(Eq. 1) $$Q^* = 0.025\exp(-40R^*)$$

where

$$Q^* = \frac{q\sqrt{s_{op}/2\pi}}{\sqrt{gH_s^3 L}}$$

$$R^* = \frac{R_c}{H_s}\sqrt{\frac{s_{op}}{2\pi}}$$

q = discharge due overtopping
H_s = significant wave height
L = ramp width
s_{op} = wave steepness, $s_{op} = H_s / L_{op}$
L_{op} = deep water wave length, $L_{op} = \frac{g}{2\pi}T_p^2$
T_p = Peak period
R_c = Crest freeboard relative to MWL

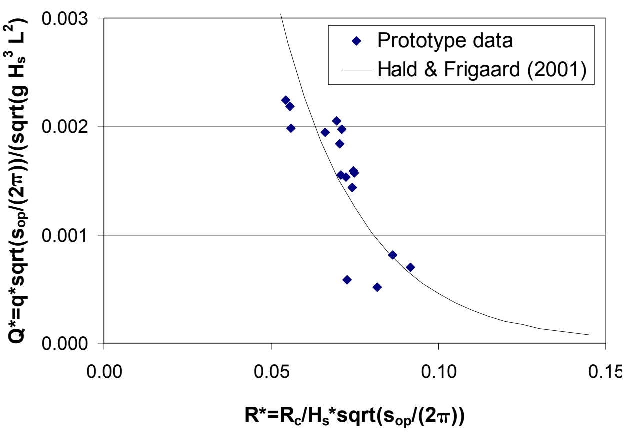

Figure 5. Comparison of preliminary prototype data and overtopping expression.

With regard to survivability a lot of experiences with especially the design of the junction between reflectors and the main body have been obtained during the first year of prototype operation. During this period the design has, due to failures, been altered, going from a delicate design where cylindrical fenders were allowed to rotate in order to act as a roller bearing, to a more rough design where the fender elements are fixed on the main body. Measurements of mooring forces in both model scale and prototype shows good correlations. The measurements underline the importance on having an elastic mooring system in order to avoid high snap-loads.

THE POWER TAKE-OFF SYSTEM

Once the overtopping water has reached the reservoir, the potential energy is harvested by the installed low-head turbines. The operating conditions of the turbines on the WD differ strongly from those in a normal river hydro power station:

- Firstly, the turbines have to operate at very low head values ranging from 0.4 m to 4.0 m, which is not only on the lower limit of existing hydro power experience, but also an extremely wide variation.
- Secondly, due to the stochastic time distribution of the wave overtopping and the limited storage capacity, the turbines have to be regulated from zero to full load very frequently.
- Lastly they have to operate in a very hostile environment, with only a minimum of maintenance being possible on an unmanned offshore platform.

Early in the project it was concluded that the turbines had to be as simple and rugged as possible, with an absolute minimum of moving parts. Thus, a design with both fixed guide vanes and fixed runner blades has been chosen. The result has been a low head turbine specially developed by the WD team and tested at the Technical University of Munich. The resulting efficiency of the single turbine is between 91 to 92 % in the relevant head and flow ranges.

CONCLUSION

A prototype of the Wave Dragon is currently, as part of the preparations towards a full size multi MW production plant, undergoing real sea testing in Nissum Bredning, Denmark. So far the preliminary testing has supported the data earlier achieved from laboratory testing of mainly hydraulic performance. Furthermore, invaluable experience has been obtained in most operational aspects, such as regulation strategies for crest freeboard and turbines, remote control of operation and testing, etc. Also problematic design details have been pointed out, and solutions tested in realistic conditions.

For further information, please visit www.wavedragon.net and www.civil.auc.dk/~i5jpk/wd/wdnb.htm.

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