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The Wave Dragon - Now Ready for Test in Real Sea

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ABSTRACT

The Wave Dragon is an offshore wave energy converter of the overtopping type, utilizing a patented wave reflector design to focus the waves towards a ramp, and the overtopping is used for electricity production through a set of Kaplan/propeller hydro turbines. During the last 2 years, excessive design and testing has been performed on a scale 1:50 model of the Wave Dragon, and on a scale 1:3.5 model turbine. The survivability, overtopping, hydraulic response, turbine performance and feasibility have been verified. Furthermore regulation strategy, grid connection technology, generator technology, and mooring systems have been accommodated to the Wave Dragon. The main conclusions from this work are elaborated, and the future plans for, and expectations to, the technology is described.

BASIC FUNCTIONING OF THE WAVE DRAGON

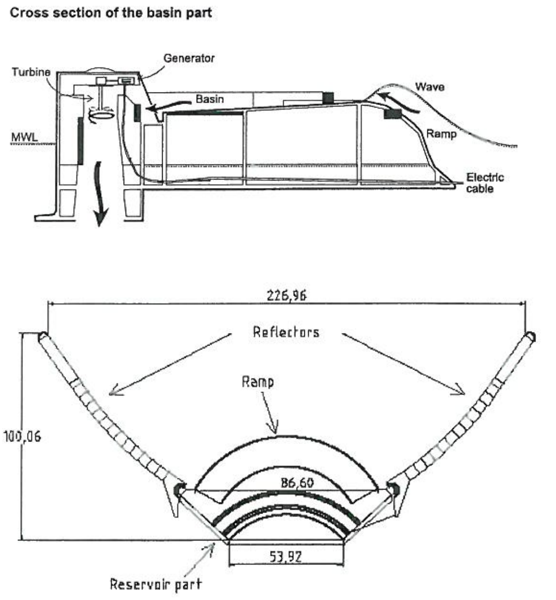


Figure 1 The Basic principle of the Wave Dragon

The Wave Dragon is a slack-moored offshore wave energy converter of the overtopping type. Each unit will be of 4 MW, located offshore at more than 20 meter water depth. The Wave Dragon is envisaged to be deployed in parks of up to 200 units, minimizing grid connection and maintenance costs, and promising a substantial contribution to the future energy supply from wave energy. The basic functioning of the Wave Dragon, patented by E. Friis-Madsen (10), (11), can be seen from Figure 1.

The Wave Dragon 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 (22) and energy capture by 70% in 3 meter significant waves (30).
- The main structure consists of a patented doubly curved ramp and a reservoir.

- A set of low head Kaplan-propeller turbines for converting the hydraulic head in the reservoir into electricity.

When the waves overtop the ramp, water is filled into the reservoir at a higher level than the surrounding sea, and this hydraulic head is utilized for power production through the hydro turbines.

The Wave Dragon consists of standard technologies combined in new ways.

The survivability of the Wave Dragon was tested at Aalborg University on a scale 1:50 model in 1998-1999, and overtopping and hydraulic behavior was tested during 1999-2000 at University College Cork. Work on turbine strategy, regulation strategy, power take-off and grid connection systems, mooring and geometrical layout, and regulation strategy has been carried out during 1999-2000. A model turbine in scale 1:3.5 has been tested at TU Munich during 2000.

SURVIVABILITY AND HYDRAULIC PERFORMANCE TESTS

In 1998-1999 the first tests on a floating model in scale 1:50 were performed at Aalborg University. The main conclusions from these tests were:

- The Wave Dragon showed good survivability when tested also for very severe seas (100-year storm in the North Sea), and even with one or two of the wave reflectors not attached (18).
- The model collected water for all sea states, and had good energy absorption, and the energy capture was best for the lower (and more common) sea states (24).
- The pitch and heave motions were undesirably large (18), (24). Based on these results, numerical modeling of the geometrical layout was performed (9).

Based on this work the model was modified, by attaching plates horizontally at the bottom of the main structure, on the front and rear parts of the vessel, increasing the hydrodynamic added mass.

A new test series were performed, and it was concluded that although the movements were reduced considerably, this did not result in significantly improved overtopping. But the forces in the wires and mooring system were reduced considerably (25).

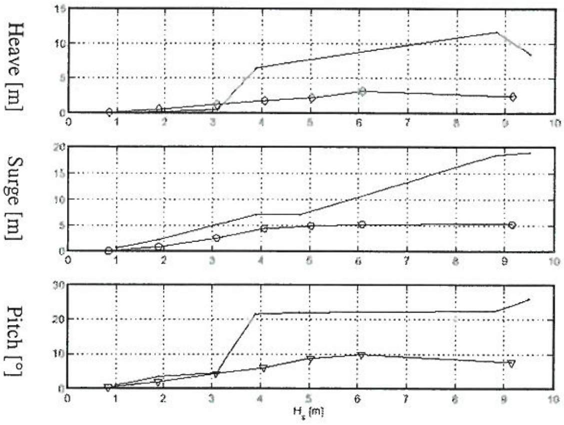


Figure 2 Heave, surge, and pitch before and after modifications to scale 1:50 model (25)

OVERTOPPING TESTS

Tests performed at University College Cork demonstrated that the Wave Dragon is not very sensitive to not heading directly into the dominant wave direction, e.g. caused by current or wind effects (30). Furthermore it was discovered that trimming (lowering the ramp relative to the rear part), increased overtopping significantly, and smoothened the variances in overtopping (30).

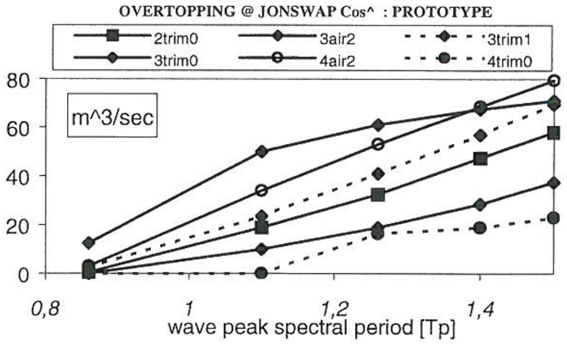


Figure 3 The effect of trim on performance (30). 'XtrimY' means that the height of the stern is A, and the front is lowered 'Y' m compared to 'X' m

This discovery may be of major importance for the turbine operation and power take-off, as decreased variance in overtopping allows for scaling down of the whole power train, with potentially considerable cost reductions.

The results from the initial test series indicated that reasonable estimates of the overtopping distribution could be obtained through a random process (24).

The random process is compiled of two steps. Firstly it is determined whether overtopping occurs and secondly the overtopping volume of the current wave is calculated. According to (24) the probability of overtopping of vertical structures and rubble mound dikes is Reyleigh distributed. The probability is basically a function of the significant wave height, H_s and the height of the freeboard R_c

Eq. 1
$$P_{ov} = 1\exp\left(-\left(c\frac{H_s}{R_c}\right)^{-2}\right)$$

where the constant c is related to the profile of the crest freeboard (c=1.21). If overtopping occurs the volume of the individual overtopping waves can be described by a Weibull distribution, with a shape parameter of 0.75 and knowledge of average overtopping discharge. The probability function of an overtopping discharge per wave Vw being less or equal to V is given by:

Eq. 2
$$P_V = P(V \leq V_w) = 1 - \exp\left(-\left(\frac{V_w}{a}\right)^{0.75}\right)$$

$$a = \frac{qT_m}{P_{ov}}$$

in which q is the average overtopping discharge, T_m the mean wave period and P_{ov} being the probability of overtopping as determined by Eq. 1.

Eq. 3
$$q = 0.017c_d\exp\left(-48\frac{Rc}{Hs}\sqrt{\frac{S_{op}}{2\pi}}\right)\frac{L\sqrt{gH^3}}{\sqrt{\frac{S_{op}}{2\pi}}}$$

$$S_{op} = \frac{H_s}{L_{op}} \qquad L_{op} = \frac{1}{2\pi}gT_p^2$$

where L is the length of the curved crest freeboard, T_p is the peak period and C_d is a reduction coefficient of 0.9 accounting for directional spreading.

Based on the measured average overtopping values, the actual amounts of overtopping occurring were described mathematically (25).

Based on Eq. 1-3 a software tool for generating overtopping time histories were developed. The simulated overtopping was found to lie within the uncertainty of overtopping measurements in the laboratory (17), (19).

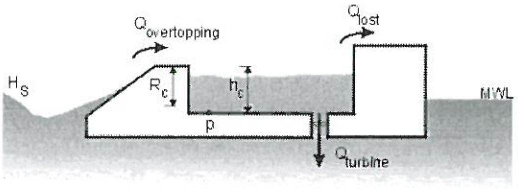
REGULATION OF THE FREEBOARD HEIGHT

Developing feasible regulation strategies for the Wave Dragon has shown to be difficult. Basically two different regulation strategies are called for:

- A regulation of the freeboard, adjusting for changing wave situations (long-term regulation)
- A regulation mechanism for starting and stopping the turbines.

The objective of the long-term regulation is to construct a reliable control strategy, allowing the freeboard height to be adjusted automatically, as the wave climate changes over time.

Idea



- Change in actual R_c^{act} to obtain optimal R_c^{opt}
- Actual R_c^{act} is measured
- Optimal R_c^{opt} can be calculated: $R_c = f(H_S, Q_0)$
  Optimal R_c^{opt}: max energy(turbine strategy, max Q_0R_c)
- What is H_S?

Figure 4 Regulation set-up

Indirectly, the overtopping and the sea state can be derived from turbine performance data, provided that the spill back in the sea can be accounted for with some general patterns. An initial approach has been to develop an algorithm of this nature (13). The stability of the algorithm has been verified through performing a number of simulations, using an overtopping simulation software tool, developed by Aalborg University (14), (25).

Being a floating model, an additional challenge to the modeling work is found in the fact that the overtopping affects the hydraulic performance of the vessel and vice versa, through the weight and movements of the water in the reservoir. This, plus the fact that the motions of the wave reflectors are interfering with the motion of the main structure, makes modeling of the hydraulic performance extremely difficult (1), (29).

The optimal freeboard crest heights for different sea states can be found from figure 5.

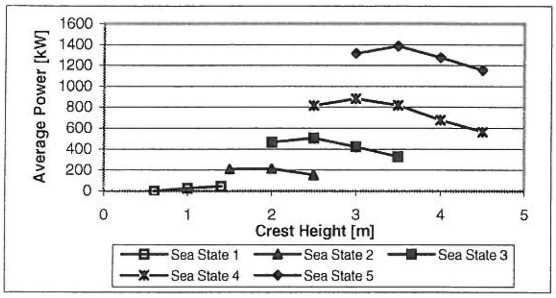


Figure 5 Average power as function of the freeboard crest height at different sea states. The figures are inclusive losses in the power train (13)

TURBINE LAYOUT

The Wave Dragon posed a number of untraditional challenges to the turbine designers and manufacturers (16). Firstly, the heads available at the Wave Dragon will be in the range from 1-4 meters. This is considerably below the heads for which Kaplan/propeller turbines are normally deployed. Secondly, the heads and flows show frequent variance, as it will change for every wave overtopping the ramp. Normally head and flow variances are handled through adjusting runner and guide vane angles, but in the case under consideration here, this strategy was not considered possible, as the frequent regulation would introduce heavy stress in the movable parts resulting in fatigue.

From theoretical and practical investigations it has been decided to deploy several small turbines of the propeller type at the Wave Dragon, to be operated at variable speed. As there exists no comparable data to these turbines, it was decided to construct a model turbine (scale 1:3.5), for testing in a conventional hydro turbine test stand in Munich, Figure 8.

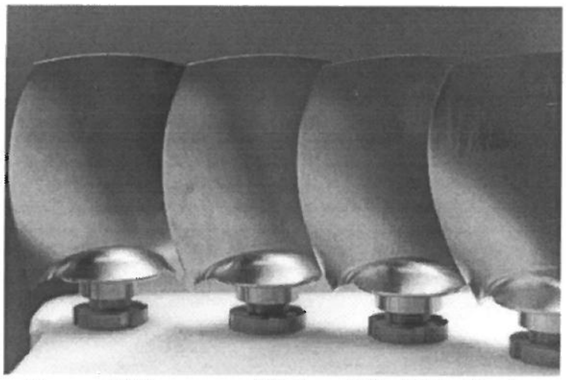


Figure 6 The runner blades of the WD- Kaplan turbine scale 1:3.5

Preliminary results have shown that the efficiencies of the model turbine design are considerably above expectations, and more important, that the span of heads and flows for which high efficiencies can be obtained, is much wider than expected. A comparison of the preliminary turbine performance derived from extrapolation and the model turbine test results is given in Figure 7 below.

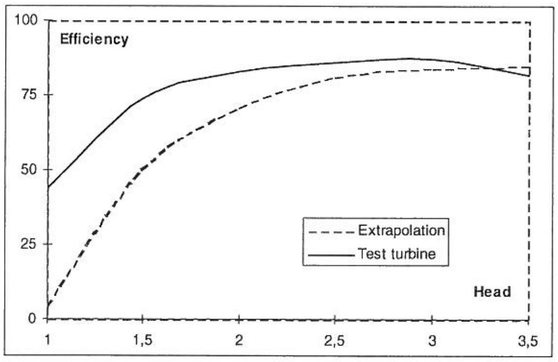


Figure 7 Fixed speed on/off Kaplan turbine w. Cylinder gate inlet - expected vs. measured turbine performance, incl. intake & outlet losses

GENERATOR STRATEGY AND POWER TAKE-OFF

Operating the turbines at variable speed means that the frequency of the power production will vary. This poses some unconditional demands to the power take-off system, involving generators controlled by frequency converters.

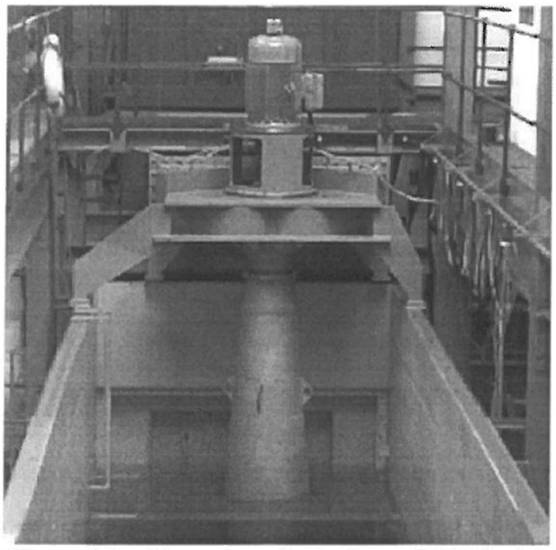


Figure 8 Turbine set-up for testing at TU Munich of WD-Kaplan turbine scale 1:3.5

The unexpectedly wide range of heads for which high turbine efficiencies can be obtained (see Figure 7), introduces the possibility of applying two different power take-off systems at the Wave Dragon. A set of turbines equipped with conventional asynchronous generators, being in operation for the head span at which turbine efficiencies are high, and a set of turbines equipped with synchronous generators controlled by frequency converters, operating at all reservoir heights. Such a solution will lower the costs of the power take-off system, as the need for power electronics is reduced.

Consulting Engineers Elsamprojekt and Balslev have performed investigations into the design of the internal power grid, and the system is currently being tested.

GRID CONNECTION

Through the Danish Power Distribution Company Eltra, studies of the power take-off system layout and grid connection requirements have been performed. The Wave Dragon is assumed to face the same system requirements, as are valid for offshore wind farms, if connected to the Danish grid (6). One such requirement is that the device must be able to reduce the production to less than 20% of max. output in max. 2 seconds, a requirement that causes some problems for offshore wind, but which is not a problem for hydro turbines. A number of other requirements on e.g. frequency variations, voltage changes or voltage jumps, voltage flicker, telephone interruptions etc. was also specified (6).

With this in mind, internal and external grid system was designed for a Wave Dragon park consisting of 50 units (200 MW), located 25 to 100 km offshore.

For locations up to 25 km offshore it would be relevant to look into the possibility of continuing the farm-internal grid directly to the shore, at a voltage of ± 50 kV DC. This yields the obvious advantage that an offshore converter substation can be dispensed with altogether. This means a considerable reduction of the construction costs and the operation and maintenance costs. In all likelihood, the service platform will have to be established irrespective of the concept chosen for general servicing of the farm, and therefore the additional expenses incurred by installing the switchgear suggested are very modest (7).

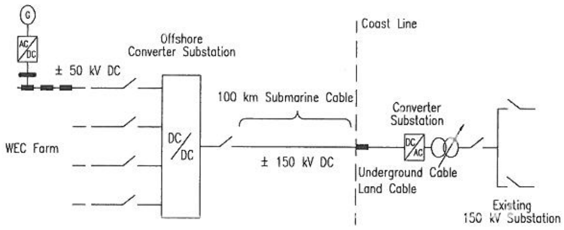


Figure 9 Transmission line - 100 km offshore (7)

For locations 25-100 km offshore there is a critical cable length to consider, rendering DC transmission the only solution possible. This calls for a step up in voltage e.g. to ± 150 kV DC, which would be a sensible voltage for a 200 MW transmission line across 100 km. The cable technique for ± 150 kV DC has already been developed and tested. A transmission system for far offshore deployment is shown in Figure 9.

An especially problematic issue has been the cable from the individual Wave Dragon units to the seabed cable. Information from an experienced offshore equipment supplier have shown that cables allowing up to 45 degrees of rotation are available, and stress tested for 50 years lifetime at the Wave Dragon. A solution allowing more freedom of rotation is possible, but will require additional research (7).

OPERATION STRATEGY AND SIMULATIONS OF ANNUAL POWER PRODUCTION

A considerable amount of work has been performed on the short-term regulation strategy. Examples of turbine regulation strategies are given in Figure 10. It was found that the optimal reservoir base level in many wave situations were quite close to the crest of the reservoir, even though this increased the spill (15), (8).

Basic specifications for a control, regulation and surveillance system have been developed by consulting engineers Balslev (4).

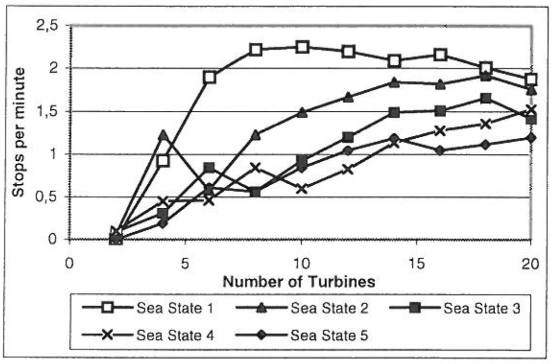


Figure 10 Turbine stops per minute as a function of number of installed turbines (8)

MOORING AND STRUCTURAL LAYOUT

The Wave Dragon is a slack-moored wave energy converter, but still the exact mooring layout is not finally decided, as it will differ between different locations. The British naval architects Armstrong Technology (2) has proposed two different solutions, the choice of which has shown dependent on a number of factors.

Option 1 would involve 4 anchor lines running from the mooring buoy into the predominant wave direction. The back end of the Wave Dragon would be tied off to a further set of anchor lines to keep it in place. This solution would not allow the Wave Dragons to weathervane more than a few degrees.

Option 2 would involve replacing the conventional buoy with a CALM buoy (Catenary Anchor Leg Mooring), which would be tied to the seabed by a spread of three groups of three lines. This solution would allow the Wave Dragon to weathervane freely.

Option 1 has the advantage of being considerably cheaper than option 2, but this will have to be added up against the reduced energy capture from non-dominant wave directions. It is to be noted that the model tests has demonstrated, that the Wave Dragon energy capture is very good, even when the vessel heading is deviating up to 45 degrees from the dominant wave direction (30), making this solution feasible for many locations.

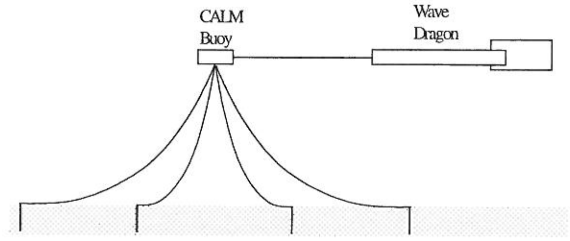


Figure 11 Example of a CALM buoy mooring system for the Wave Dragon (2)

Furthermore the choice of mooring system will have to take into account the amount of rotation allowed by the transmission cables (7).

FEASIBILITY

The feasibility of the Wave Dragon will be evaluated during the coming months, based on the results obtained through the tests performed during the last two years.

Although a final feasibility study is not available at the time writing, a number of initial observations deserve to be mentioned.

A first generation full-scale prototype will cost approximately 11 MEUR, and at the current state of development, such a prototype will have an estimated production price of 0.11 EUR/kWh (27). These figures are obviously still covered with some amount of uncertainty, but given continued research and development, the chances of achieving non-excessive production prices are good. Obviously a first generation prototype will not immediately be price competitive with wind power, but it is worth noting, that the Wave Dragon economy resembles that of an average Danish wind turbine from 1984 (28). In the price mentioned above there has not been included the reduction caused by mass production neither has the learning effect from producing more units.

FUTURE EXPLOITATION

The Wave Dragon is undoubtedly one of the wave energy converters, which are most suitable for large-scale offshore deployment. This appears to fit into the general heading of the renewable energy sector, where the power companies are taking an increasingly active role, and where several major offshore wind power projects is currently in the making. From a grid operator point of view, large-scale wave energy converters as the Wave Dragon yields a very interesting potential, as the peak production period is delayed to the wind power peak production period. The introduction of large-scale wave power parks therefore levels out the quite large fluctuations in the tied power supply from wind power. Therefore the development is currently followed with some interest from the Danish systems operator Eltra.

Based on the results from the JOULE-CRAFT project, a number of design modifications have been introduced (3), (12), (27) for the design of a coming scale 1:4 model. For example a new ramp profile has been tested (20), with good results. These changes will be evaluated based on a new wave tank test program (12). At the same time the consortium behind the Wave Dragon has been enlarged with major companies within the shipbuilding and construction industries. This consortium is currently engaged in raising funds for designing, building and testing of a scale 1:4 model, in Nissum Bredning (large Danish inlet) where the Danish Wave Test Station is situated and where the waves are comparable to the North Sea in scale 1:4 (21). These activities are planned to take off in the second half of 2001. If the results from this test series live up to expectations, a first generation full-scale prototype can be deployed from 2005, allowing commercial exploitation to start.

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