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Development of the Wave Energy Converter – Wave Dragon

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Abstract

The development of the wave energy converter Wave Dragon (WD) is presented. The WD is based on the overtopping principle. Initially a description of the WD is given. Then the development over time in terms of the various research and development projects working with the concept is described. This is followed by a description of the different parts of the structure together with a description of how this specific design has been chosen. Plans for the future development are finally presented.

Key words:
wave energy converter, wave overtopping, physical model tests, hydro turbines.

Introduction

In recent years wave energy has gradually been brought into focus as it has become clear that fossil energy resources are limited and cause large environmental problems, e.g. CO_2 pollution. In the light of this a number of different wave energy converters have been proposed. In Denmark the government decided to appropriate 40 mill. DKK (approx. 5.4 mill. EUR) to the development of wave energy devices during a period of four years, 1998-2001, and the European Union (EU) also supports the development through the JOULE program. Among the wave energy concepts receiving financial support from both programs is the WD.

Presentation of the Wave Dragon

The WD is a floating wave energy converter of the overtopping type. It is developed by Erik Friis-Madsen from the Danish engineering company Löwenmark Consulting Engineers.

The WD can briefly be described as consisting of three components (see Figure 1, 2 and 3):

- Two wave reflectors for focusing the waves.
- A ramp leading the waves to the reservoir by overtopping.
- A number of low head turbines for converting the hydraulic head and flow into electricity.

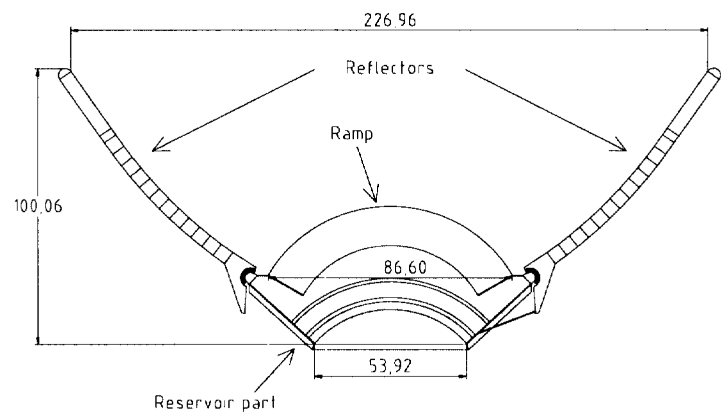

Fig. 1 Plan view of the Wave Dragon. Measures are in m.

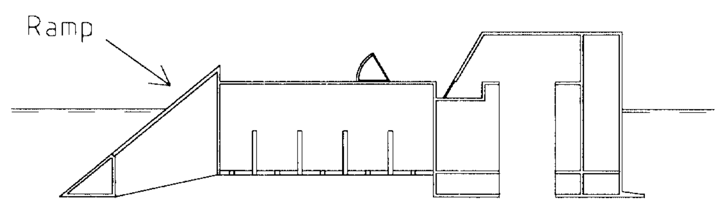

Fig. 2 A cross section of the reservoir part of the Wave Dragon.

The main parts of each of the two wave reflectors are made of 12 equal straight elements. In addition, a longer element with less draught is attached at the end. Transition elements connect the reservoir and the main part as well as the main and the ending part of the wave reflectors. Curvature of the wave reflectors is obtained by introducing an angle between the elements. The upper parts of the reflectors are made of a steel shell, while the lower parts are constructed of reinforced concrete.

The reservoir part of the WD is constructed of reinforced concrete or steel. Reinforced concrete design is expected to be the most economical, and furthermore a heavy structure is desirable in order to reduce the movements. The bottom of the reservoir part is an open grate allowing water to enter the body. The draught is adjusted by a pressurized air system. The WD is designed to survive even if the ballast tanks should loose the air pressure.

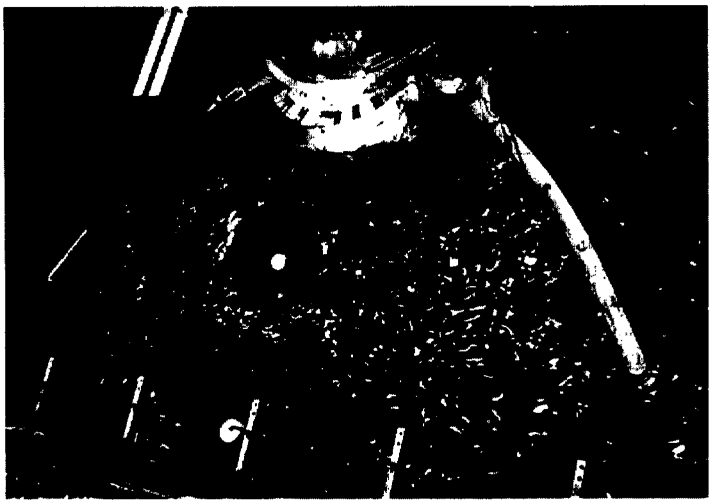

Fig. 3 Photo of the floating model of the WD in the in the 3-D wave tank at Hydraulics & Coastal Engineering Laboratory, Aalborg University.

The reservoir itself is constructed in such a way that its area is only a limited fraction of the total area of the reservoir part at the water line. When the reservoir fills with water overtopping the ramp, the draught of the WD increases. Typically 1 m increase of the water depth in the reservoir induces a 0.5 m larger draught. Consequently the head available for the turbines decreases.

In the reservoir permeable plates are placed to damp waves in the reservoir itself generated by the overtopping and motion of the main part of the WD.

The turbines in the reservoir are placed relatively high in order to facilitate maintenance and a siphon effect is utilized to lead the water through turbines in normal operation. When maintenance and service is necessary, the siphon effect is eliminated. However, using this principle also means that it is crucial that the reservoir is never completely emptied during normal operation, but is always kept relatively full. An alternative configuration with a vertical propeller turbine surrounded by a cylindrical gate is also being investigated. In both cases an active control of the turbines is necessary.

A number of hawsers are fastened to the wave reflectors and the main part and are joined at a moored buoy. Presumably the buoy will be gravity anchored, however, other systems such as pile foundation or suction anchors are under consideration.

The WD will most likely be placed at 20 to 50 meters water depth, which is equivalent to 25 - 100 km from the coastline in the Danish part of the North Sea. To minimize the cost of transmission of the power to the coast it is necessary to deploy numerous WD units in a group. A typical wave energy power plant of the WD type is expected to consist of 50 – 200 units.

The history of the Wave Dragon concept

The inventor, Erik Friis-Madsen (EFM), initiated the development of the WD in 1986. In the early years he developed the principle of the WD, and in 1995 an application for patent was submitted, Löwenmark (1995). Both a Danish and an European patent for the WD have been obtained since then, Friis-Madsen (1999a) and Friis-Madsen (1999b).

During the period 1995 – 19999 a number of preliminary studies of structural layout, financial aspects, geometry, optimal choice of turbine configuration and movements of the WD were carried out, Birckner (1995), Rolsted (1996), Nielsen & Kofoed (1997), Hansen & Jørgensen (1998) and Andreasen & Lauridsen (1999).

Using the findings of these studies, the WD design was slightly modified and a test programme formulated. This test programme, financed by the Danish Wave Energy Program, consists of thorough investigations of movements of the floating structure, mooring forces, forces in the reflectors, overtopping/amount of captured energy and survival in extreme wave conditions. These tests were carried out at the Hydraulics and Coastal Engineering Laboratory, Aalborg University, 1998-1999, using a floating 1:50 scale model of the WD built by the Danish Maritime Institute.

The tests showed large pitch motions resulting in less overtopping than expected. Subsequently the WD was further developed, resulting in an improved hydraulic performance.

In 1997 an application for the EU Exploratory Award was formulated, Löwenmark & Ossberger (1997). The resulting research application and feasibility study were published 1998 (Löwenmark & EMU (1998) and Löwenmark et al. (1998)).

As a continuation of the work performed under the Danish Wave Energy Program and on the basis of the research feasibility study, the EU has granted funding for a project called *Low-pressure Turbine and Control Equipment for Wave Energy Converters (Wave Dragon)* under the Non-Nuclear Energy RTD Program (JOULE–CRAFT). The total budget for this project is 1 mill. EUR of which the EU funds 50 %.

The objective of this project is to optimize the hydraulic performance, structural design, design of configuration, control and regulation of the turbines and design of electrical component and connection to grid. Aalborg University (Denmark), University College Cork–HMRC (Ireland) and Löwenmark (Denmark) focus on the hydraulic performance, structural design is dealt with by Armstrong Technology (UK), design of configuration, control and regulation of the turbines are done by Ossberger Turbinenfabrik (Germany) / Kössler GmbH (Austria), Hälleryd Turbiner AB (Sweden), Veteran Kraft (Sweden) and Technical University Munich (Germany), and design of electrical component and connection to grid is done by Balslev(Denmark), Belt Electric (Denmark) and Elsamprojekt / Eltra (Denmark). EMU (Denmark) is coordinator of the project.

Current stage of the development

In the following the current layout of the different parts of the WD and the investigations leading to these are described.

Geometry of reflectors

Nielsen & Kofoed (1997) have carried out an evaluation of the shape of the reflectors. In this study numerical calculations were done on the efficiency of the reflectors in terms of the amplification of the wave height for a range of different layouts. In light of these calculations the layout of the reflectors shown in Figure 1 was chosen by the inventor EFM. The numerical calculations showed that wave height is increased 30 - 75 % by reflectors (depending on the wave situation). These calculations were confirmed by model tests performed with a fixed model (length scale 1:50) of the WD at Aalborg University, see Figure 4 where the measured effect of the reflectors is illustrated.

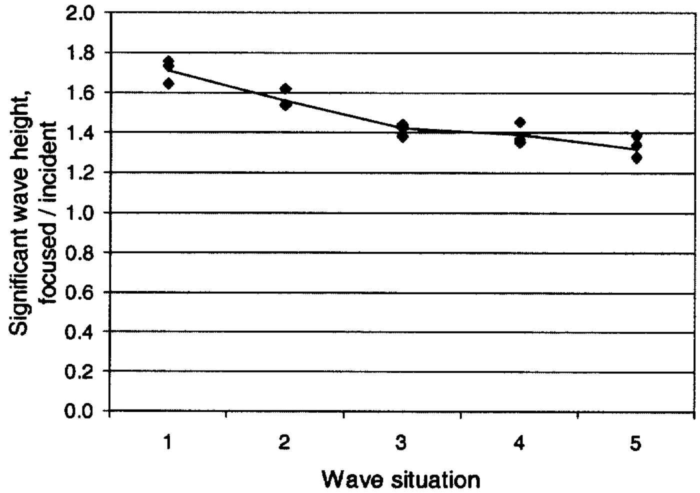

Fig. 4 Effect of reflectors in terms of ratio between significant wave height outside reflectors (incident) and significant wave height the location of the reservoir (focused). From model tests performed by Nielsen & Kofoed (1997)

Geometry of overtopping ramp

After the waves are focused by the reflectors, they will overtop the ramp and enter the reservoir. It is therefore essential that the ramp allows as much overtopping as possible to the highest possible level, which also implies that wave breaking on the ramp should be avoided. This is contrary to what is normally the target when designing slopes in connection with other marine constructions, e.g. breakwaters where the purpose is to reduce overtopping as much as possible. Nielsen & Kofoed (1997) evaluated different shapes of the overtopping ramp as an experimental parametric study. Generally speaking, parameters like the cross section shape, curvature in the plan, draught and crest freeboard are important parameters, but in the performed model tests the emphasis was on the influence of change of the cross section shape and the crest freeboard. In order to investigate whether it was possible to increase the overtopping tests were performed using different slope angles and curvatures of the ramp profile. Furthermore, as the WD is a floating structure, the draught of the slope was limited to approx. 30 % of the water depth.

The slope of the ramp must be relatively steep in order to prevent wave breaking on the slope. From the performed model tests with linear ramp profiles no significant differences in the overtopping were found for a slope angle between 35° and 50°, while increasing the angle to 60° resulted in a reduction of 20 – 30 % of the overtopping compared to a slope angle of 40°. Tests with curved ramp profiles showed no significant differences with respect to overtopping. However, only a limited number of tests with curved ramps were performed.

Investigation of movements

Kofoed & Frigaard (1999) and Sørensen, H. C. & Friis-Madsen, E. (1998) investigated the movements of a floating model. This showed that movements of the reservoir part of the WD are very small for wave situations covering 80 - 90 % of the time offshore in the Danish part of the North Sea (significant wave heights lower than 3 m). However, the tests also showed significant heave and pitch movements for wave situations with larger waves, and even though these wave situations rarely appear, it is important that the WD behaves appropriately as the energy density is high in these cases. The reason for this is that the natural periods in heave and pitch motion were close to peak periods in the wave situations with significant wave heights greater than 3 m.

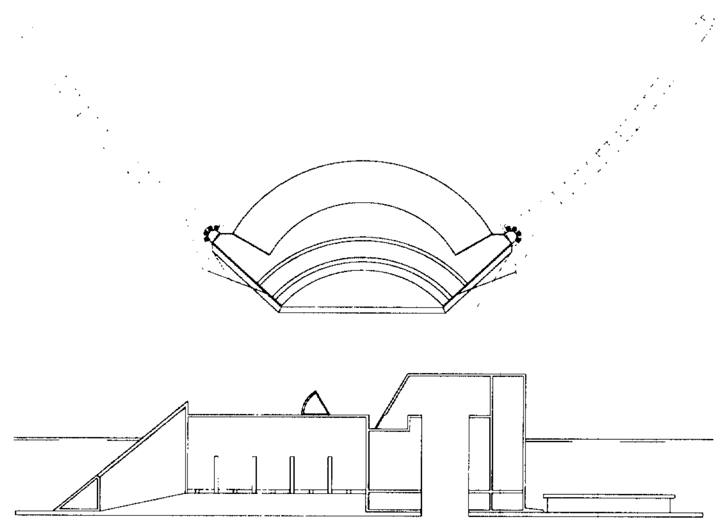

Fig. 5 Plan view and cross section of the ramp and reservoir part of the Wave Dragon after modifications.

Fig. 6 Photo of reservoir part of floating model taken from above after modification (bottom plate added).

Frigaard et al. (1999) found that modifications like changing the mass moment of inertia, the metacentre height and the mass centre could double the natural period for the pitch motion. Furthermore, it became apparent that the pitch response could be decreased by changing the setup of the mooring cables and by extending the platform backwards. In light of this a decision was made to modify the model. Figure 5 to 7 shows the model layout after modifications.

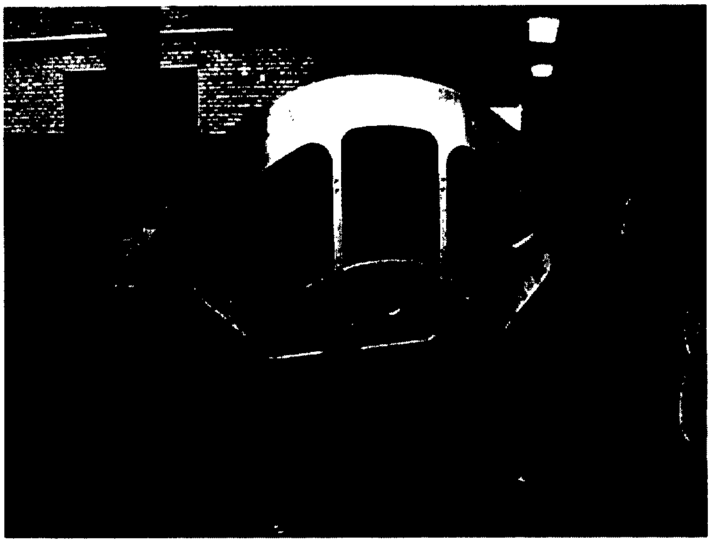

Fig. 7 Photo of reservoir part of floating model taken from below after modification (bottom plate added).

The modifications shifted the natural period in pitch from 13 to 20 sec., and the movements where reduced significantly as shown in Figure 8, Martinelli & Frigaard (1999b).

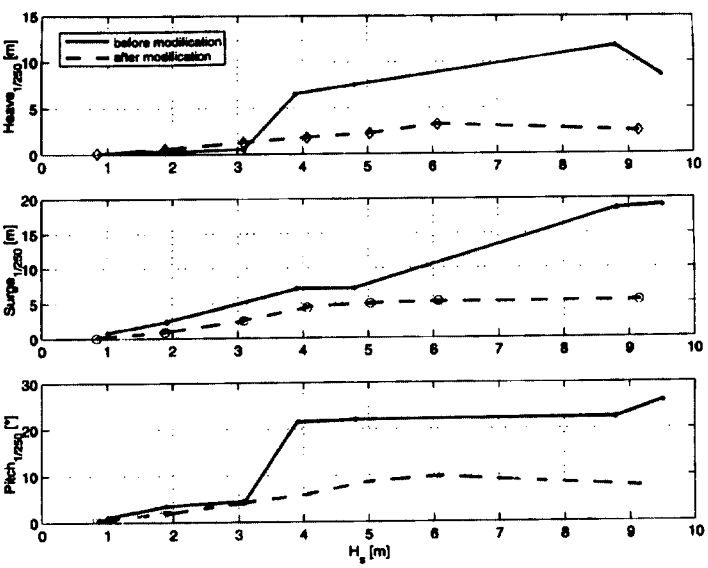

Fig. 8 Comparison between extreme displacements measured before and after modifications.

Even though the largest movements constitutes no serious risk of failure of the WD and the design therefore seem to be acceptable, smaller movements are still desirable in order to increase overtopping. Generally speaking the wave elevations and the movements of the reservoir are in phase resulting in less overtopping for greater pitch and heave. Figure 9 shows heave for the front and rear of the reservoir, respectively. The front moves more than the rear. Evidently the centre of rotation in pitch should be moved forward. Ideally it should be on top of the slope. However, this does not seem possible.

Investigation of forces

Kofoed & Frigaard (1999) measured forces in the mooring system and in selected parts of the structure using the floating model. However, special attention was not paid to the scaling of the stiffness of the mooring system as no detailed information about this was available at the time. Undoubtedly, the mooring system was too stiff and therefore the measured forces represent an upper limit.

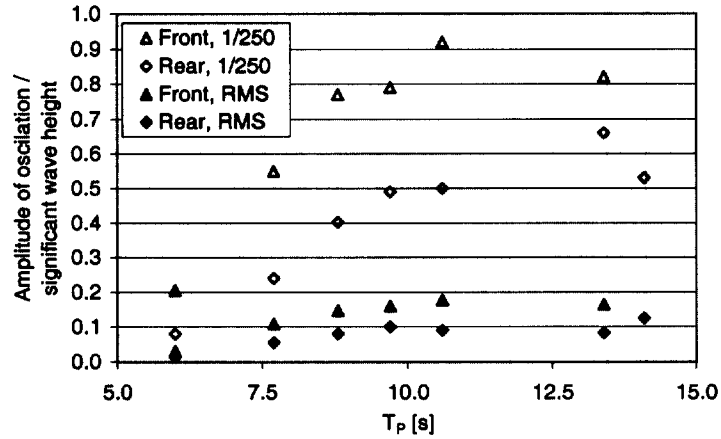

Fig. 9 Root mean square (RMS) and 1/250th amplitudes of oscillation of front and rear crest oscillations normalized by the significant wave height as a function of the wave peak period. After Martinelli & Frigaard (1999b).

The setup of the model tests and the layout of the mooring cables are shown in Figure 10.

In the succeeding tests Martinelli & Frigaard (1999b) introduced elasticity in the mooring system by inserting a spring between the buoy through which the WD is connected to the mooring system and the fixation point. The stiffness of the cables between the different parts of the WD and the buoy was adjusted. All of these changes in the setup resulted in a remarkable reduction in the measured forces (35 – 90 % reduction). In light of this investigation a mooring system has been proposed by Armstrong Technology (1999).

The axial and shear forces in the connection between the reflectors and the reservoir part were also measured in both test series. Generally, the forces measured in the first tests were greater than in the following ones although an increase in the vertical forces were measured. This is caused by the increase in the pre-stressing of cables between the reflectors and the reservoir part. Increase of the pre-stressing level resulted in a reduction in the movements in pitch, but also increased the vertical forces.

Survival in extreme wave conditions.

During the tests with the floating model the WD was subjected to extreme wave conditions with a return period of more than 50 years (significant wave heights greater than 10 m). The WD survived these severe wave conditions. The tests were performed using both long and short crested waves.

Investigation of overtopping

From model tests of ramp profiles using a fixed 2-D model of the ramp subjected to 2-D waves Nielsen & Kofoed (1997) suggested an exponential expression for describing the overtopping rate. This expression was verified by tests using a 3-D fixed model of the WD for wave situations it typically will be subjected to.

In model tests performed with the floating model both before (Martinelli & Frigaard (1999a)) and after modifications (Mar-

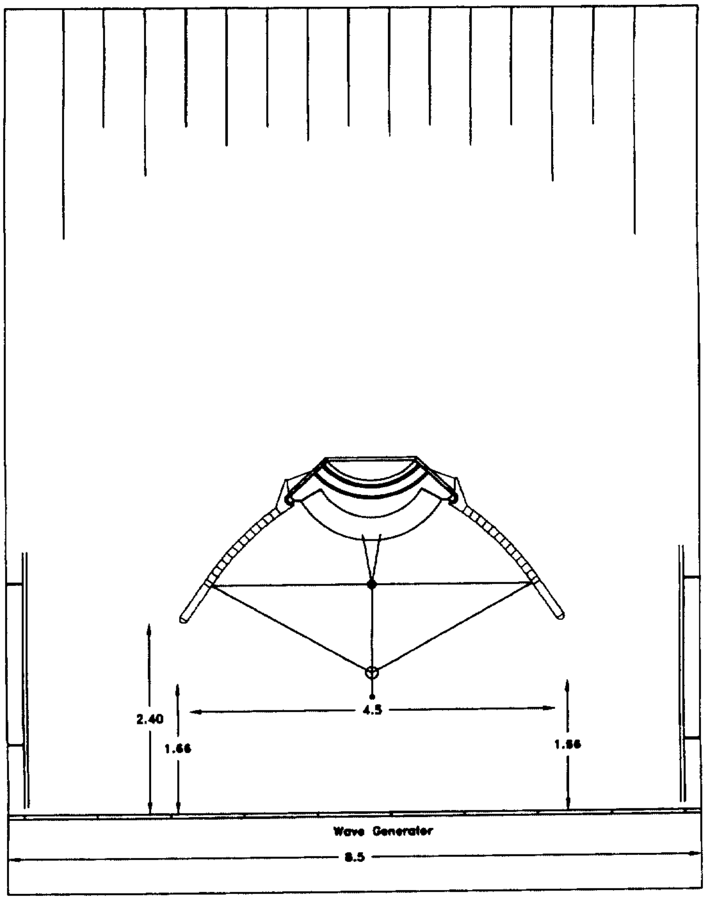

Fig. 10 Setup of model tests in laboratory also showing the layout of the cables between the different part of the WD and the buoy.

tinelli & Frigaard (1999b)) it was found that eq. (1) gives the best description of the mean overtopping rate per unit width of the ramp q ($[m^3/s/m]$) when the WD is subjected to 2-D waves (the focusing effect of the reflectors is included in the formula).

$$\frac{q\sqrt{\frac{s_{0p}}{2\pi}}}{\sqrt{gH_s^3}} = 0.017e^{-48\frac{R_c}{H_s}\sqrt{\frac{s_{0p}}{2\pi}}} \tag{1}$$

where

H_s	significant wave height (outside the reflectors).
R_c	crest freeboard.
s_{0p}	wave steepness defined as $s_{0p} = \frac{H_s}{L_{0p}}$.
L_{0p}	peak deep water wavelength defined as $L_{0p} = \frac{gT_p^2}{2\pi}$.
T_p	peak wave period.
g	acceleration of gravity.

This expression is only valid for wave situations with a peak period well separated from the natural period of the pitch movements (max. 80 %) where the movements of the reservoir part are limited. This is the case for wave situations with significant wave heights equal to 3 m or less (corresponding to peak periods of up to 9 s). For wave situations with significant wave heights greater than 3 m eq. (1) overestimates the overtopping rate increasingly with increasing significant wave heights (to as much as a factor 2 for a significant wave height of 5 m). This emphasizes the importance of increasing the natural period of the pitch motion.

For both model test series on the floating model a decrease in the overtopping rate was observed when subjecting the WD to 3-D waves. The observed decrease amounted to 25 – 35 % for directional spreading of 10° to 25°.

Using eq. (1) for calculation of the amount of energy captured in the reservoir and assuming that the water level in the reservoir is kept close to the crest freeboard by controlling the turbines, it is found that the average yearly production is 5.4 GWh for a typical location in the Danish part of the North Sea. In this case the fact that directional spreading will decrease the overtopping is disregarded and it is assumed that the problem of too large pitch motions in wave situations with a significant wave height greater than 3 m is solved.

Currently a separate project focusing on maximization of potential energy in overtopping is ongoing at Aalborg University, Kofoed (1999). In this project a wide range of ramp profile shapes are tested in order to establish expressions for estimation of overtopping rates and obtained potential energy as a function of wave situation, crest freeboard, draught, slope angle and ramp profile shapes. Utilizing the results from this project, it is expected that an increase in the overtopping rate for the WD can be obtained by adjusting the ramp profile shape, slope angle, draught and crest freeboard.

Design improvements by means of changes in weight distribution and pressure distribution in air chambers are tested at University College Cork–HMRC. The general idea is to move the centre of rotation (pitch) forward and thereby increase overtopping by decreasing vertical movements of the front slope even though the pitch movements is still the same.

In continuation of the model tests performed with the floating model, a computer programme for simulation of the power production of the WD is being developed, Jakobsen & Frigaard (1999). This simulation programme calculates the output of electrical energy from the WD for given wave conditions, turbine configurations and basic geometrical properties of reservoir specified by the user. In the calculation of the overtopping time series used as input to the turbines, it is assumed that run–up levels on the ramp are Rayleigh distributed and overtopping occurs when the run–up level exceeds the crest level. The volume in each of the individual overtopping waves can be described as a Weibull distribution, Van der Meer & Janssen (1995). The Weibull distribution is a function of the mean overtopping rate as given in eq. (1). An example of the output from a simulation is shown in Figure 11.

This version of the programme can only handle a constant number of turbines in operation and the turbines are presumed to operate at a constant propeller speed. An advantage of controlling the number of turbines in active operation and also their speed in accordance with the water depths in the reservoir is expected, Holmén (1999), LHM-TUM (2000a) and LHM-TUM (2000b). The next versions of the computer programme will be able to simulate "automatic control" of the turbines in different ways depending on the chosen strategy for the turbine layout and regulation (simple on/off or on/off plus speed control).

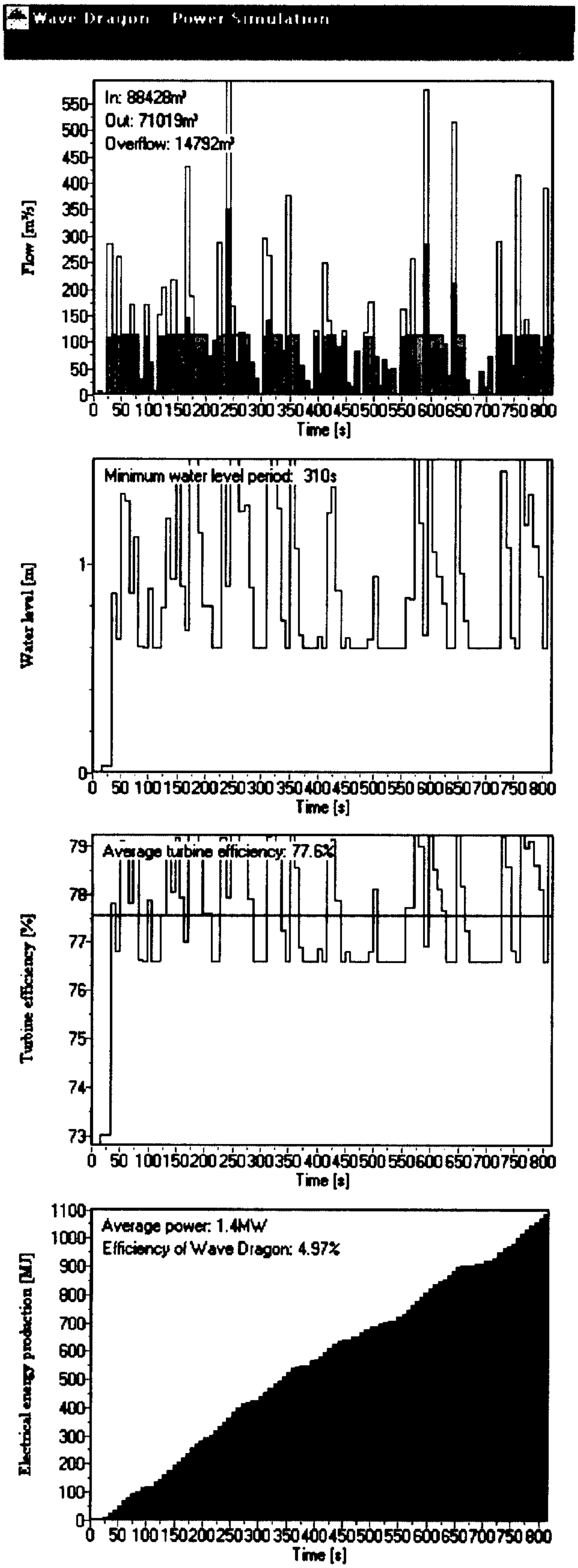

Fig. 11 Results from a simulation (arbitrarily chosen turbine configuration). (a) Water flow for each time step. (b) Water level in reservoir. (c) Turbine efficiency for each time step. (d) Accumulated energy for each time step.

Turbine design and configuration

One of the important objectives of the EU financed JOULE-CRAFT project is the choice of optimal turbine design and configuration. The partners involved in this subject are currently working on different turbine configuration principles. One of them is to use a few turbines with pitch–controllable blades (which are relatively expensive). Another principle is to install a large number of smaller (and less expensive) turbines with fixed pitch propellers and then shut them on and off as needed to follow the varying flow. Finally, it is also an option to use fixed pitch turbines and control the propeller speed so it follows the head for the turbines by connecting the generator to the grid through a frequency converter.

In order to investigate which turbine configuration is the best, primarily in terms of cost–benefit, a large number of simulations using the previously mentioned computer programme with a large variety of turbine configurations are planned.

Simulations carried out by LHM at the Technical University Munich have indicated that 4 MW distributed on 16 turbines is a reasonable installed effect.

Supported by the Danish Wave Energy Program a new propeller type turbine will be developed this year. The new turbine will be optimized for the low levels of head available in overtopping wave energy devices like the WD. The turbine is expected to reach higher efficiency in this low and varying head range than it is possible with propeller turbines of normal design. The test of the new turbine in scale 1:3 will be performed by LHM at the Technical University Munich. Also numerous tests with variable speed of the turbine are part of the test programme.

Connection to the grid

Regarding the issue of getting the power to the seashore and connecting to the grid considerations already given to the transmission from the Danish offshore wind farms are used as a starting point since the situations are comparable. It is considered necessary to step up the voltage at each single unit before transmitting the power to a common transformer station for the whole plant (up to 200 WD units) in order to avoid considerable losses because of the distance between each of the units and the transformer station. For the transmission of the power to the seashore from the transformer station, yet another step up in voltage is necessary, again to avoid considerable losses because of the great distance between the transformer station and the seashore. Both AC and DC solutions are under consideration for this connection.

In order to carry on with more detailed analysis of the connection to the grid more precise information on properties of the power supply from the turbines and generators is needed. Therefore further work on this issue is postponed until after the turbine configuration has been chosen.

Future development

The tests in Aalborg and Cork have shown that the WD will behave well with respect to heave and pitch in 80 – 90 % of the operating time (dependent on the chosen site in the North Sea). The mentioned drop–off in efficiency in wave situations with significant wave heights of more than 3 m is primarily caused by large excursions of the crest freeboard. In the EU project this problem is expected to be solved by further modifications of the existing model (more ballast will be added in the front and thereby the center of gravity will be moved). At the same time the damping plate under the ramp should be cut away and the ramp extended downwards a few meters.

Parallel to the described tests of different ramp profiles plans are being made to perform studies with new or partly new models in 2D and 3D wave basins to establish the optimal geometrical design of the wave reflectors and the reservoir part itself. A revision of the feasibility study by Löwenmark & EMU (1998) to be concluded by the end of year 2000 is expected to confirm that the investment per installed kW will be around 2.5 kEUR and the predicted price for WD-power from the North Sea will be around 0.1 EUR/kWh. It should be mentioned that the power levels at other locations offshore of Europe, e.g. west of the coast of Ireland, are more than 3 times the values in the Danish part of the North Sea. A WD scaled for and deployed at such locations is therefore expected to be able to produce power at a considerably lower price.

After conclusion of the EU project the building of a 1:3 scale model is being planned for launch at a test site in inner waters somewhere in Denmark. This is considered a necessary step before building a full-scale prototype in order to achieve experience with controlling the turbines, necessary maintenance, etc. One of the important issues to be investigated in these tests is also the influence on the pitch and heave movements of changing the air pressure in the different buoyancy compartments.

Acknowledgements

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