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Wave Dragon, prototype wave power production

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Wave Dragon is a floating wave energy converter working by extracting energy principally by means of overtopping of waves into a reservoir. A 1:4.5 scale prototype has been sea tested for 20 months. This paper presents results from testing, experiences gained and developments made during this extended period. The prototype is highly instrumented. The overtopping characteristic and the power produced are presented here. This has enabled comparison between the prototype and earlier results from both laboratory model and computer simulation. This gives the optimal operating point and the expected power of the device. The project development team has gained much soft experience from working in the harsh offshore environment. In particular the effect of marine growth in the draft tubes of the turbines has been investigated. The control of the device has been a focus for development as is operates automatically for most of the time. This has led to improvements in the power take off, trim control and stability of the device.

Keywords: Wave Power, Overtopping, Production, Prototype

Introduction

The Wave Dragon is a floating offshore wave energy converter of the overtopping type. A full scale Wave Dragon designed for an appropriate climate would have a installed power of 4-11 MW. A prototype scaled at 1:4.5 of a North Sea model and rated at 20 kW has been tested in Nissum Bredning, a large inland waterway in Denmark from May 2003 to January 2005.

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.

Figure 1: The Wave Dragon Nissum Bredning Prototype.

The prototype has all the features of a 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.

Availability

The Wave Dragon Nissum Bredning Prototype has been tested in real sea for approx. 2 years. During the period May 2003 to December 2004 the availability of the system has been continuously increasing to up to 80% at the last part of the period.

Monthly operating experience of the power production systems from May 2003 until end of 2004 is summarised in Figure 2. This reflects time logged in the PLC system where the Wave Dragon’s power production system has been in active operation, either

- “Continuous operation” (green) mode which covers longer periods where the prototype has been in automatic production mode. Not necessarily aiming at optimum power output.
- When carrying out specific test runs (labelled “Testing”, yellow). This covers tests of control systems and tests of hydraulic response, i.e. effect on floating level and stability.

The additional time has been spent on:

- Re-construction and re-configuration activities (labelled “Re-construction”, grey)
- Waiting time (labelled “Out of operation”, red). This covers as an example holidays and simply evenings and nights in the periods without a working automatic fire extinguishing systems (insurance question). In these periods power production has been stopped.

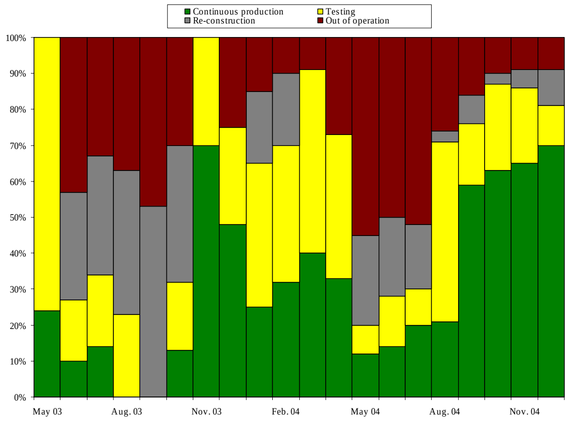

Figure 2: Availability of WD-NB over the period of real sea testing.

The Wave Dragon’s power production system referred to covers turbines, generators, inverters and rectifiers plus PLC system.

A close to 100% availability has been achieved for other Wave Dragon systems, like the automatic floating level and stability system and the remote control and communication systems.

From the 1st October 2004 to 9th January 2005 measurements were made almost continuously on the prototype. Sample periods of 30 minutes were chosen - 300 to 500 waves. This prevents too much scatter within a result set, while preventing a loss of definition due to fast wave build up in Nissum Bredning which has a relatively short fetch. Of the approximately 4800 such sample periods during the time 3969 records were made including the most important measurements. Of these 1577 had high quality enough measurements to allow full time series analysis of all the flows, and of these 247 had significant wave height great enough to give some power production. This relatively low proportion is due to the fact that the platform was not fully ballasted – for safety reasons – and thus it never floated at a level low enough to permit overtopping at very low wave heights. These 247 sample periods are those shown in this paper.

Power capture

The water flow overtopping the ramp and the hydraulic power which passes through the turbines are the two main measures used to compare power production performance at this stage. The overtopping flow is compared to predictions based on earlier laboratory tests. The hydraulic power passing through the turbines accounts for the lower head across the turbine than the crest freeboard. The electrical power generated by the real turbines is recorded. A third measure of power is the estimated electrical power, this is the power which would have been produced by the hydraulic power if the dummy turbine flow had passed through a functioning turbine and if the speed control of the PM generators was working optimally.

The overtopping flow is defined as the flow which passes through the turbines, ignoring any spill from the reservoir back to the sea. The individual turbine flow is calculated from the turbine characteristic (Keller et al, 2001) as a function of head and rotational speed. Pressure transducers in the reservoir measure the head.

Kofoed et al, 2006, presents the overtopping relationship for the Wave Dragon based on the results from tank testing of a scale model. It is clear that there is a wave length dependency on the overtopping. The form of the non-dimensional units Q* and R* depend on the wave steepness, based on the breaking criterion. The slope of the ramp of the Wave Dragon is rather steep; to avoid loss of energy during breaking. A better model for the rate of overtopping over a low crested, non-breaking and floating structure is desirable.

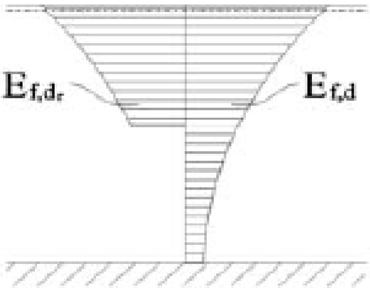

Figure 3: Vertical distribution of energy in water column

A different method to include the frequency dependency of the waves into the non-dimensional form is given by Kofoed, 2002. Its physical basis has more relevance for this case of a floating overtopping device, and is shown above in Figure 3. The average overtopping rate Q_N is non-dimensionalized as normal and modified by the ratio of the energy in the water column between the free surface and the draft of the device to the total energy in the water column.

$$Q_N = \frac{1}{\lambda_{d_r}} \frac{\overline{Q}}{W\sqrt{gH_S^3}} \qquad (1)$$

Where:

$\overline{Q} =$ overtopping rate [m^3/s]

$H_S =$ Significant wave height [m]

$W =$ Ramp width 21.6 m [m]

$\lambda_{d_r} =$ Ratio of energy between free surface and device draft $E_{f,dr}$ to incident wave energy $E_{f,d}$. [m]

$$\lambda_{d_r} = 1 - \frac{\sinh(2k_p d(1-\frac{d_r}{d})) + 2k_p d(1-\frac{d_r}{d})}{\sinh(2k_p d) + 2k_p d}$$

$k_p =$ Wave number at peak period [m^{-1}]

$d =$ Depth of water [m]

$d_r =$ Draft of device [m]

Figure 4 shows the overtopping flow relationship, between the Q_N and the relative crest freeboard (Rc/Hs). The predicted overtopping from the old theory (Hald and Frigaard, 2001) is presented to compare the flow through the turbines measured on the prototype. The scatter in these results is due to the difference in the form of the relationship, an exponential best fit line is plotted for these. The measured flow through the turbines is plotted, with the size of the markers indicating the proportion of time the reservoir was within 0.01 m of full. The larger points show a full level between 50 % and 75 % of the time.

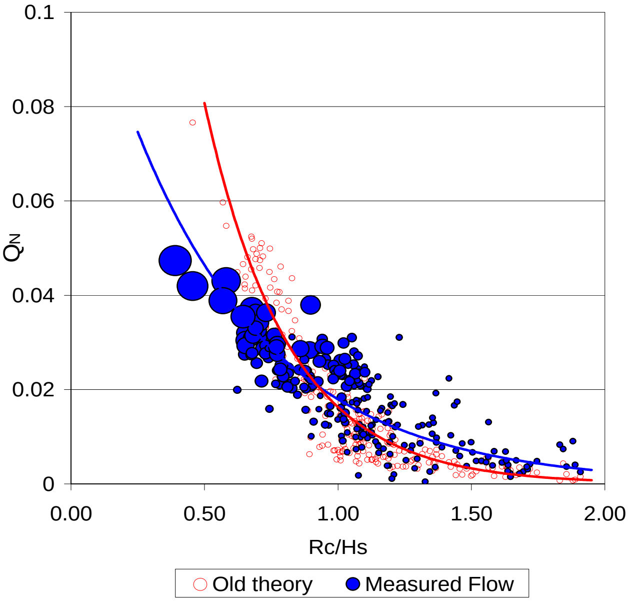

Figure 4: Overtopping flow

When the crest freeboard was high (Rc/Hs > 1) the overtopping rate was generally higher than predicted from the old formulation. In lower crest freeboard the water flow through the turbines was considerably less than the predicted flow. In these cases the reservoir was very close to the full level for over half the period. It is probable that this loss in flow is due to considerable spill from the reservoir back to the sea. This is a greater problem than expected as the flow capacity of the prototype was less than designed. This was caused by an incorrect setting of the inverter speed control, causing the generators to spin at a below optimal speed, and also three of the generators were out of order for this period. The flow capacity of the prototype is thought to have been around 65% of the designed capacity.

Figure 5 below shows the average power produced in various sea states. The 'Produced' power is the electricity delivered from the PM generators on the working turbines. The 'Estimated' Power is the electrical power which would have produced if the dummy turbines had been producing at the same efficiency as the actual turbines, and if the inverter speed control had been functioning correctly. The 'Hydraulic' power is the power of the water passing through the turbines.

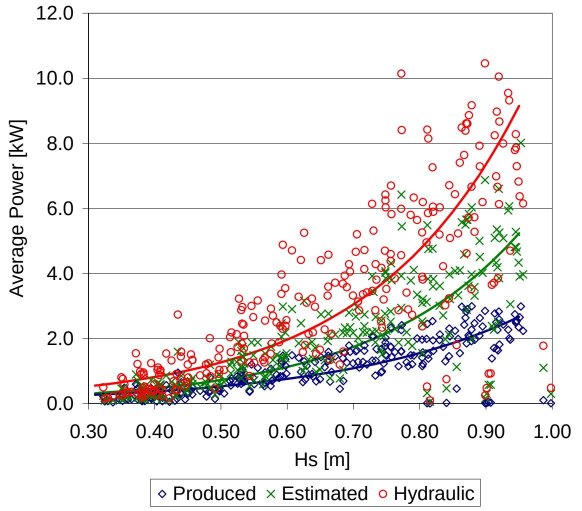

Figure 5: Energy captured

There is a significant difference between the hydraulic and the electrical energy. This is due to the low overall efficiency (0.3-0.65 depending on head) of the scaled down turbines and generators, mainly due to fixed losses such as bearing friction. In the full scale the overall efficiency of this stage will be between 0.80 and 0.85. The total levels of energy production are also low as the platform was mostly operated at a too high floating level and with insufficient turbine capacity at the lower levels.

Figure 6 shows the ratio of energy captured by the Wave Dragon. The 'Hydraulic' efficiency is defined as the ratio of the average power of the water through the turbines to the theoretical incoming wave power across a width equal to the Wave Dragon ramp width (see Falnes, 2002). The 'Production' energy is the ratio of the average electric power generated by the operating turbines to the same theoretical incoming wave power.

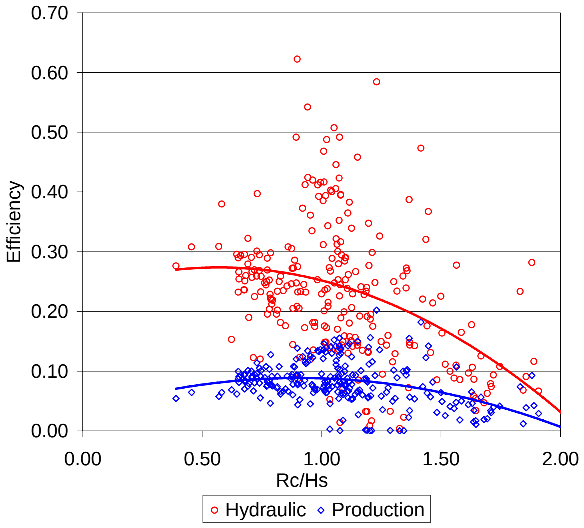

Figure 6: Efficiency

From this diagram it appears that the optimal relative crest freeboard for energy production is around Rc/Hs = 1.0. The hydraulic efficiency was lower at the lower crest levels due to the lack of turbine capacity. Production efficiency is much lower at these points as here much of the flow passed through the dummy turbines and so did not generate any electricity. Previous simulation work has shown an optimal relative floating level of Rc/Hs 0.7-0.8 with full capacity. This is still believed to be accurate.

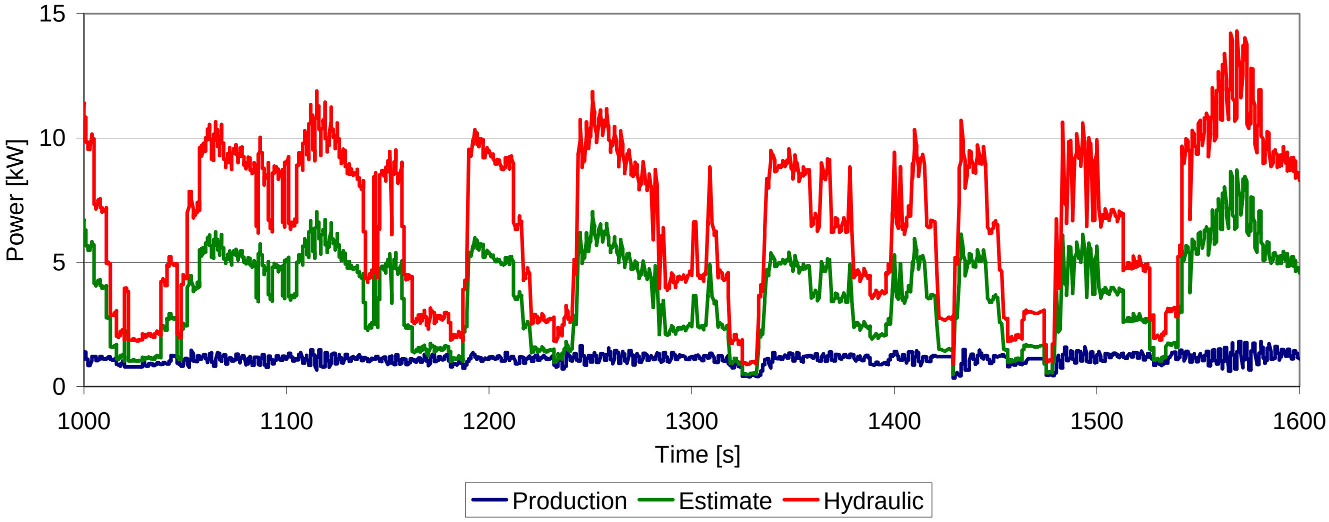

Figure 7: Time series of sample record

Currently work is being conducted by Knapp in the Technical University of Munich on the simulation program. This work is trying to simulate the production of the prototype Wave Dragon, operating as it did during this period, in particular taking into account the faulty turbine speed behaviour. This will enable a good comparison of whether the energy captured is realistic, and how large the improvement in production would be if the turbines had been operated at full capacity.

The time series shown in Figure 7 shows a 10 minute sample from the record of December 16th 2004 at just after 9 am. The corresponding point lies roughly in the middle of the records and was of a sample with Hs = 0.62 m and a floating level of 0.45 m. There is a great deal of dummy turbine activity here, which does not show up on the actual electrical production. The power is quite smooth, with a ratio between the peaks and troughs of the estimated power of around 3.

Soft issues

In operating and maintaining the device during the testing period, the development team has gained invaluable “soft” experiences. This can be grouped into the following categories:

- Maintenance: the experience has shown that access to the device, transportation of pieces of equipment and work on board are only possible in relatively calm weather conditions. This can be planned on the basis of weather forecasts, but major operations need to be planned including a withdrawal scenario for the case that the work needs to be stopped due to bad weather.
- Corrosion: for many stationary steel parts, a conventional epoxy paint system has proven sufficient. For some of the moving parts, however, more expensive corrosion resistant materials needed to be used. This proved to be of particular importance in parts of the power train such as turbine shafts and bearings. For strongly stressed

components, stress corrosion cracking needs to be considered.

- Marine growth: On components underneath the waterline, heavy marine growth has accumulated within a short time. In some components this is acceptable, as it just means additional weight. In others, such as the turbine draft tubes, the layer of growth increases the friction losses and reduces the performance. This problem was solved by using suitable non-toxic anti-fouling coatings, which proved very efficient.
- Electrical equipment: A number of components that were classified IP66 failed although they were just exposed to rain and wind. The spray of sea water is carried into places that seem to be relatively well sheltered. The lesson learnt is that sensitive equipment must assembled with utmost care to make sure the sealing properties are maintained, and it needs additional protection against splash and spray exposure. Also the effect of corrosion attack onto the sealing surfaces needs to be considered.

Overall, there were no problems that could not be solved, but a lot of problems that were not anticipated.

Conclusion

The real sea testing of the Wave Dragon 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 smaller component failures. All of these have been investigated, and technical solutions have been found.

An enormous quantity of data has been collected during the testing period, which has not yet been fully analysed. However, the work done up to now has confirmed that the performance predicted on the basis of wave tank testing and turbine model tests will be achieved in a full scale prototype.

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Further information

More information can be found on the project at the website www.wavedragon.net.

References

Falnes J. *"Ocean Waves and Oscillating Systems"*, Cambridge University Press, 2002

Frigaard P. and Kofoed J.P. *"Power production experience from Wave Dragon prototype testing in Nissum Bredning: 2003 to 2005"* Aalborg University, 2005.

Hald, T. and Frigaard, P.: Forces and Overtopping on 2. generation WD for Nissum Bredning. Phase 3 project, Danish Energy Agency. Project No. ENS-51191/00-0067. Hydraulics & Coastal Engineering Laboratory, Aalborg University, Denmark, 2001.

Kofoed J.P. *"Wave overtopping of Marine Structures – Utilization of Wave Energy"* Aalborg University, 2002.

Kofoed J.P., Frigaard P., Friis-Madsen E. and Sørensen H.C. *"Prototype testing of the wave energy converter wave dragon"* Renewable Energy 31, 2006.

Keller J., Rohne W., Böhm C. and Knapp W. *"Wave Dragon, Development and Tests of a Variable Speed Axial Turbine"* TU München, 2001.