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Renovation of the Wave Dragon Nissum Bredning Prototype

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ABSTRACT

This paper presents developments of the Wave Dragon, a large offshore wave energy converter. A prototype has been tested in a real sea environment for over 20 months. During 2005 the plant has been in harbor for a major overhaul of several of its components. The motivation for the upgrades, the laboratory testing procedure and the design and manufacture are described. The modifications are complete and the prototype is scheduled to be deployed at a higher energy site in December 2005.

KEY WORDS: Wave Energy; Prototype Testing; Scale Effects; Overtopping.

INTRODUCTION

The Wave Dragon is a floating offshore wave energy converter of the overtopping type. A full scale Wave Dragon designed for the North Sea would have a installed power of 4-11 MW. A 18.2 kW prototype has been tested in Nissum Bredning, a large inland waterway in Denmark since May 2003.

Figure 1: The Wave Dragon Nissum Bredning Prototype.

After this period of testing much information has been gained about the main components of the Wave Dragon, it is now to be deployed to a higher energy site within the Nissum Bredning area. Before redeployment several of the components have been upgraded, renovated and improved. The most noticeable of these is the joint between the long reflector arms and the main body. Issues with the robustness of the previous design for the joint necessitated replacing it with a ball and socket type joint. This new design has been extensively tested on a 1:51.8 scale model in the wave basin facilities at Aalborg University.

The manufacture of this joint is now complete and fully instrumented. Other upgrades include refurbishment of the low head hydro turbines and re-ballasting of the reflector arms. The Wave Dragon prototype is now ready to be redeployed.

THE WAVE DRAGON CONCEPT

The Wave Dragon consists of three main elements:

- Two wave reflectors. Attached to the central platform these act to focus the incoming waves. Laboratory tests have verified numerical simulations showing their effect of increasing the wave height. This has been shown to improve the energy captured by approximately 100 % in typical wave conditions by Kramer and Frigaard (2002).

- The main platform. This is a floating reservoir with a doubly curved ramp facing the incoming waves. The waves overtop the ramp which has a variable crest freeboard 1 to 4 m. Underneath the platform open chambers operate as an air cushion maintaining the level of the reservoir.

- Hydro turbines. A set of low head Kaplan turbines converts the hydraulic head in the reservoir into electricity.

Waves overtopping the ramp fill the 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.

An advanced pneumatic system is used to adjust the floating level of the Wave Dragon. By allowing the main platform of the Wave Dragon to be raised and lowered the rate of overtopping can be controlled. The floating height is set to maximize energy captured for a given significant wave height, with a higher setting in large sea states. The time scale for this is approximately 250 wave periods.

The many hydro turbines on the Wave Dragon allow the flow out of the reservoir to be controlled too. The turbines are progressively started and stopped to ensure the reservoir is as close to full as possible, thus maximizing the available hydraulic head, and energy captured. The time scale to open the turbine cylinder gate and accelerate the turbine to operating speed is less than 1 wave period.

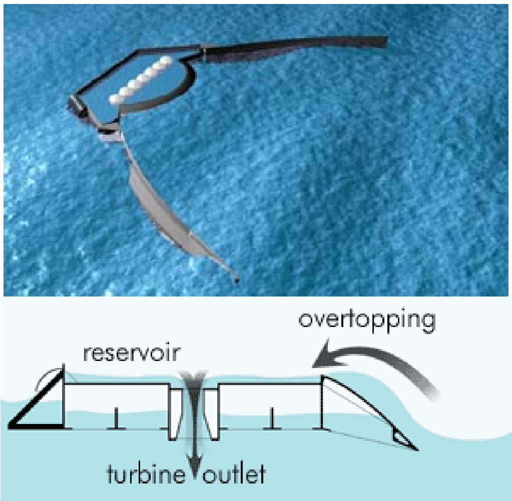

Figure 2: The Basic Principle of the Wave Dragon.

From 1998 to 2001 extensive scale testing and design of many aspects of operation was conducted. A 1:51.8 scale model was tested at Aalborg University by Kofoed et al. (2000). This led to a substantial redesign of the platform shape, optimizing the ramp profile for energy capture and the reservoir to minimize the platform motions. The low head Kaplan turbines were developed and tested at the Technical University of Munich. This lead to a design with fixed angle guide vanes and rotor blades, and with variable speed drive see Knapp (2005b).

The prototype testing at Nissum Bredning has developed the design and tested aspect which could not be tested in small scale. A major aspect is the automatic control system, maintaining the floating height, keeping the platform level and operating the turbines optimally. Operation in a sea environment has also been tested, with the corresponding marine fouling, environmental studies and maintenance requirements. Still in this scale some aspects cannot be fully studied, in particular the mooring system. The CALM buoy system intended for the full scale is modeled by compliant polypropylene and Nylon mooring lines attached to a fixed pile.

A first full scale demonstrator Wave Dragon is planned to be deployed in the waters off Wales in early 2007. Currently environmental surveys are underway in order to gain the required consents and the design has begun. Future projects are in their early stages for deployments in the Danish North Sea, Portuguese waters and Hawaii.

PROTOTYPE TESTING

From July 2003 to January 2005 testing has been conducted on a 1:4.5 scale prototype Wave Dragon in real sea environment at Nissum Bredning. Figure 3 shows the location of Nissum Bredning (indicated by the ellipse), a broad area of salt water separated from the North Sea by two tongues of land. A scale of 1:4.5 was chosen as the wave climate within the area corresponds well to a 4.5 scaled down version of the North Sea wave climate.

Figure 3: Location of the Nissum Bredning Prototype.

The prototype tested at Nissum Bredning has a total mass (including water ballast) of 237 tonnes and the distance between the reflector tips is 58 m.

Figure 4 shows the average wave density in Nissum Bredning. The upper arrow is the position where the prototype has so far been tested. The lower arrow is the most exposed site, where the prototype will be redeployed to.

The previous tests have examined the functionality and power capture of the machine. The device was grid connected at the first location, and thus it become the world's first wave energy converter situated offshore. Frigaard et al. (2004) examined the overtopping measurements of the device and Kofoed et al. (2005) has reported on other general findings from this initial testing phase.

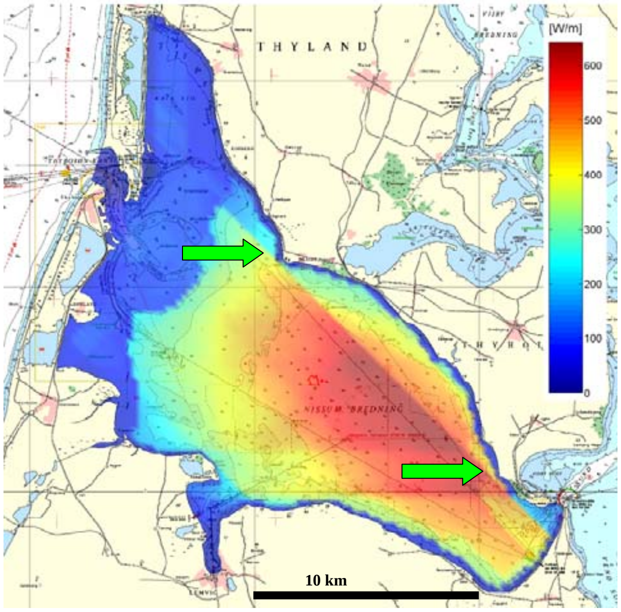

Figure 4: Energy density in Nissum Bredning. The two locations where the prototype will be placed are shown by arrows.

Unfortunately on the 8th January 2005 a large storm hit Northern Europe with ten minute average wind speeds of over 33 m/s. This 100 year event triggered a failure in a force transducer connecting the mooring lines of the Wave Dragon to its anchoring pile. The Wave Dragon stranded on a beach around 400 m from its original site. It suffered very little damage during the episode. After it was re-floated it was taken to the harbor where the work has been conducted.

In the higher energy site the power production to the grid will be greater. As it in a less accessible position the prototype will have to operate with its independent control system with less human intervention. The teething troubles which occurred at the first site have been overcome so this will be possible.

REFLECTOR JOINT

The joint between the reflectors and the main platform has been a source of trouble with the Wave Dragon prototype. The previous design with rubber fenders between the reflector and the platform suffered from a lack of robustness with failures occurring due to minor irregularities in sea states well below design specifications. The maintenance requirements of the previous design would also be too high for the full scale Wave Dragon.

The new design of joint is designed to increase robustness to minor failures in the tension line mooring system, and to lower maintenance costs. A ball and socket is chosen to resist forces in three directions by restricting the degrees of freedom at the joint from six to three.

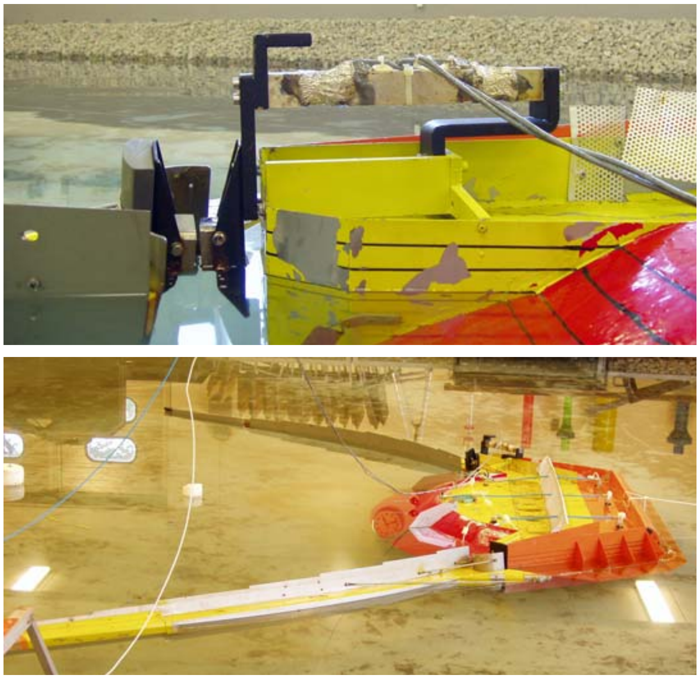

Figure 5: Test setup with 1:51.8 scale model and force transducer measuring shear force at joint

The 1:51.8 scale model of Wave Dragon, used in previous tests was re-equipped with ball joints between the reflectors and the main platform. Testing was conducted in the wave basin facilities at Aalborg University. Irregular two and three dimensional waves were produced which following the JONSWAP spectrum, a variant of the Pierson-Moscovitz spectra standard for the North Sea. The results were scaled to the prototype size and a full sized Wave Dragon according to the Froude number as shown in Table 1. Comparisons made between the prototype results and previous model tests show that this scaling is valid, only minor scale effects occur.

Table 1: Scaling ratios between model, prototype and full scale.

Unit	Scaling	Model - Prototype	Model - Full Scale
Length	λ_L	11.5	51.8
Time	$\lambda_L^{0.5}$	3.4	7.2
Force	λ_L^{3}	1.5×10^3	1.4×10^5
Power	$\lambda_L^{3.5}$	5.2×10^3	1.0×10^6

Initial tests confirmed that the highest position of the joint gives the best stability for the arm. Described in Tedd, Friis-Madsen and Frigaard (2005) these tests continued to measure the forces in the joint and its motions when unrestricted.

Figures 6 and 7 show the results from these tests with values scaled to the North Sea. The graphs show the average of the 1/250 highest peak forces for the axial and shear components. During a thirty minute test this is roughly equivalent to the average of the eight highest values measured, and is used to reduce scatter. The forces measured are in line with, and slightly lower than the measurements on the previous design.

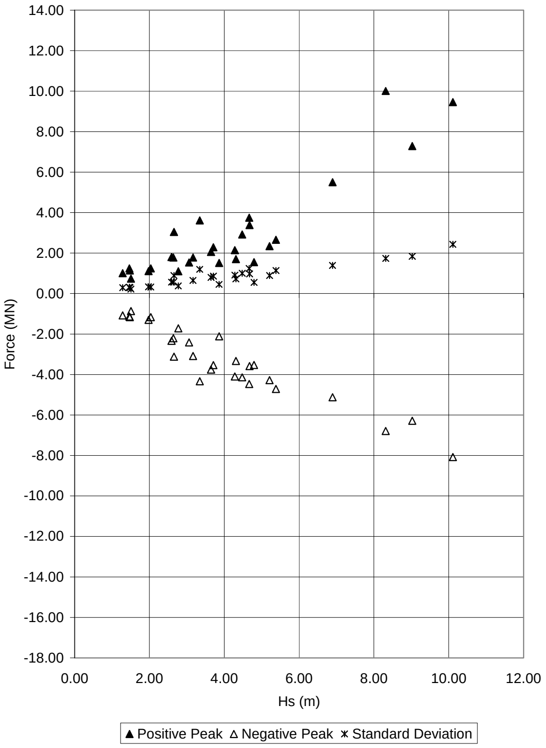

Figure 6: Axial force at joint

The motions of the arm were recorded using ultrasonic measurement system. With no other restrictions apart from the mooring lines the roll motion of the reflector was found to be the most significant. The RMS roll angle was up to 10 degrees with extremes at ± 15 degrees.

The large roll motions of the reflector arm were felt to be quite dangerous for the system as they could likely cause large wear and fatigue failure. The Wave Dragon inventor Erik Friis-Madsen proposed adding hydraulic cylinders to the joint. Connected to a generator these would act to dampen the motions and also allow power to be extracted from the roll motion of the reflector.

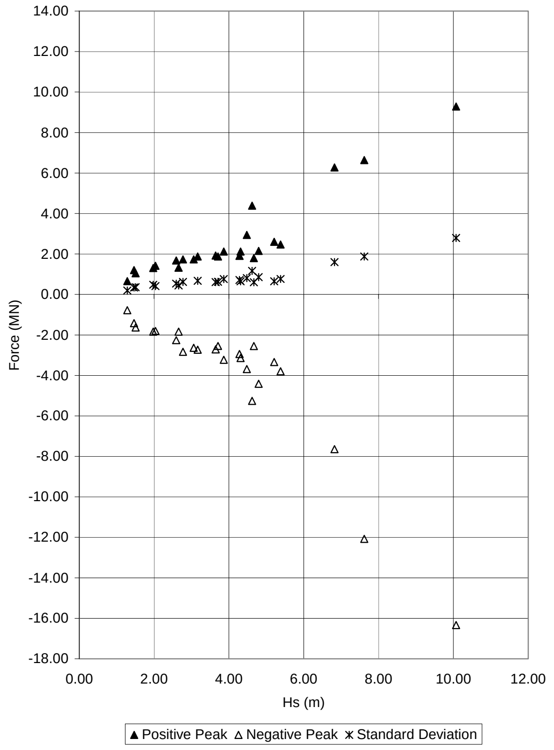

Figure 7: Shear force at joint

It is a significant challenge to model this hydraulic cylinders on such a small scale as the sticking friction in such a small cylinder is great. The solution used was a custom made Perspex cylinder and piston of diameter 33 mm. This, filled with water and connected with a thin (8 mm inner diameter, 2 – 5 m long) pipe to a reservoir gave a system allowing varying damping ratio. Tests on this measuring the moment applied by the cylinder to the reflector and the velocity of the piston were used to design the hydraulic power take off system.

Figure 8 shows the 1/250 maximum and minimum peak roll moments applied to the reflector for three different damping ratios. The roll motions of the reflector were reduced by a factor of between 2 and 3. The average energy absorbed by the reflector was measured at up to 65 kW in North Sea scale in operational states.

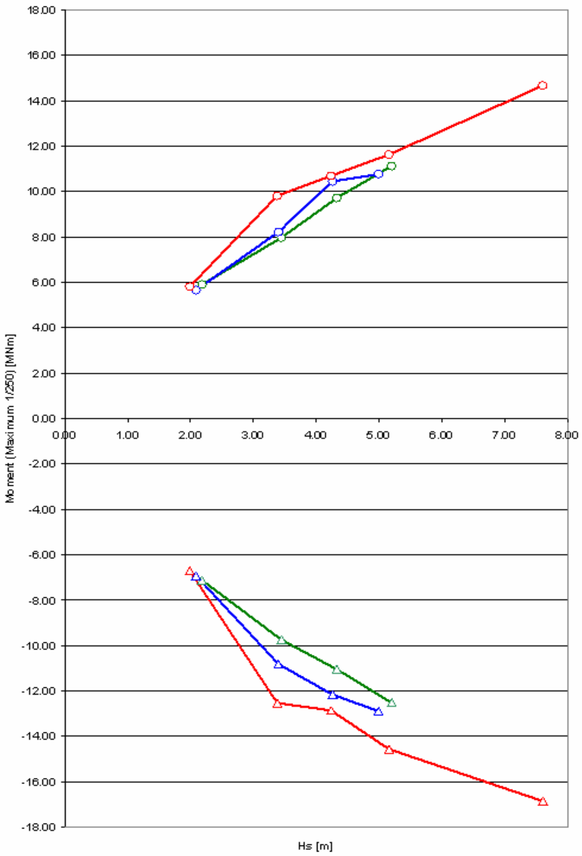

Figure 8: Roll moment on the arm.

This is for a rather over-damped system, by tuning it is anticipated that up to 250 kW will be possible to be extracted. However it must be noted that as will all oscillatory systems the power flow is very irregular with peak values over 5 times the mean. A time history of the power dissipated in the model cylinder is shown in Figure 9. This is described in full in Tedd and Kofoed (2005).

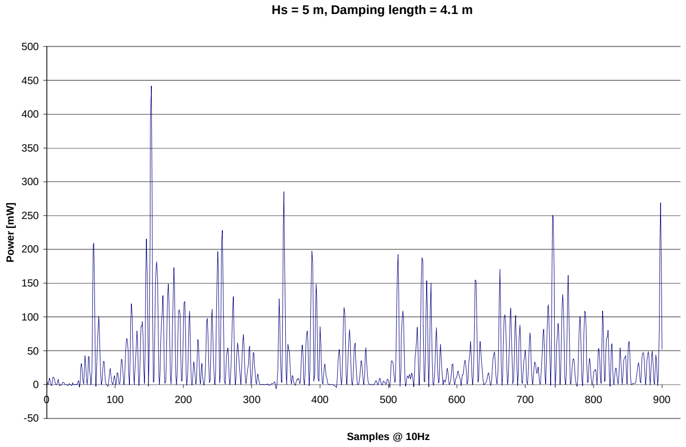

Figure 9: A typical 100 s record of power dissipated in model damping cylinder.

On the prototype the joint is constructed from a cast steel ball with PTFE bearing pads. A short cylindrical section fixes this to the reflector. The ball is encased by the socket which will be fixed to the platform at sea. The whole joint is encased by a rubber bellow to keep out sea water and prevent corrosion. In case of a leakage the bellow is filled with pressurized air.

Figure 10: Manufactured joint and fitting on main platform.

The short cylindrical section connected to the ball joint has been instrumented with strain gauge roses. As it is a simple geometric shape these strain readings will allow the forces in the joint to be calculated. In connection with a force transducer mounted in the mooring line to the reflector, it will be possible to calculate the shear force at any point of the reflector.

The hydraulic damping system is made with two pistons, mounted between the platform and the upper part of the reflector. The are positioned to mainly reduce the roll motions of the reflector, however they will also act for the roll and sway motions. The high pressure water is stored in a reservoir and from there is used to run a 24 V DC generator. The reservoir will act as a buffer and smooth the power produced.

RENOVATION OF TURBINES

While the Wave Dragon has been in harbor, much work has been conducted on the turbines and their permanent magnet generators (Knapp 2005a). While the Wave Dragon was stranded the six cylinder gate turbines (including the draft tubes and generators) were lifted off the platform.

While on dry land the turbine draft tubes were inspected. There was a large variation in marine growth with almost none on the tubes painted with non-toxic anti-fouling paint and around 4 cm of growth on unpainted tubes. The rotors which obviously have much higher velocity flows past them had no growth.

During the prototype testing the seals of the thrust bearings failed. The bearing has been redesigned and four had been replaced while the platform was at sea. The remaining three have now also been replaced. An inspection hatch was also fitted to all the cylinder gates.

Figure 11: Reinstallation of turbine.

After the replacement of the turbines their characteristics were tested by pumping water into the Wave Dragon platform. The mechanical, hydraulic and electrical efficiencies of the power train (from hydraulic head to electric power from the permanent magnet generators) were found to be 85 - 92 % at the operating head range.

BALLASTING OF THE REFLECTORS

The typical reflector cross section for a full sized Wave Dragon is shown in Figure 12. The vertical face reflects the wave and the box section provides the buoyancy, stability and stiffness to the arm. Unlike the concrete full scale Wave Dragon the steel construction of the prototype requires extra ballasting.

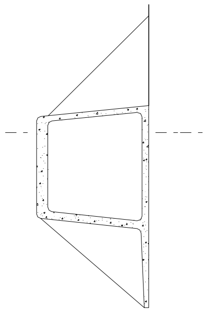

Figure 12: Typical simplified cross-section of reflector.

In the initial design polystyrene foam slabs were fixed to the vertical sides of the box section. The reflectors were then ballasted with water to obtain the correct draught. After almost two years at sea the foam was found to be severely damaged. The large air gap allowed the ballast water to move around in the chambers. The correct ballast is now known and the sections have been fitted with a larger volume of foamed polystyrene placed at the top of the section. This improvement will significantly improve the roll stability of the arms.

PLC SYSTEM

A Programmable Logic Controller (PLC) is used on the Wave Dragon to control the floating position of the platform and the turbines for optimal power take-off. Over the years several modifications and improvements have been made to this control system.

While the Wave Dragon has been in harbor more significant modifications have been conducted. The system has been upgraded to use readings from new pressure transducers positioned in the buoyancy tanks and the reservoir. Also much work was conducted to improve emergency procedures to ensure that the prototype can continue unsupervised.

CONCLUSIONS

During 2005 the Wave Dragon prototype has undergone a major overhaul. This necessitated a extensive laboratory testing procedure of the new joint between the main platform and the wave reflectors.

The plant is now ready to be redeployed in Nissum Bredning. It is instrumented to allow results from the sea testing to be compared with the laboratory expectations.

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FURTHER INFORMATION

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

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