Turbine Control Strategy using Wave Prediction to Optimise Power Take Off of Overtopping Wave Energy Converters

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Turbine Control Strategy using Wave Prediction to Optimise Power Take Off of Overtopping Wave Energy Converters.

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Abstract

This paper presents the control strategy used on Wave Dragon overtopping wave energy converter. The nature of overtopping requires that for optimum performance the water level in the reservoir must be controlled by controlling the turbine outflows. A history of the simulations performed is included. The concept of including an element of prediction, based on wave records a short distance in front of the Wave Dragon, is introduced. Initial simulations indicate a possibility to increase production by 5 to 10 % with knowledge of the next five overtopping events. It is intended to further this research with more computer simulations and tests on the 1:4.5 scale prototype Wave Dragon.

Introduction

This paper presents the problem of controlling the reservoir water level of an overtopping wave energy converter. The history and methodology used in the Wave Dragon project is shown to explain a method of optimising the power take off. Future work in adapting the strategy to account for short term prediction of waves is introduced.

All wave energy converters of an overtopping type must have a strategy to control the level of water in their reservoir in order to maximise the power output of the device. If the level of the reservoir is much below the crest freeboard then energy is lost as the overtopping water falls to a lower head. However if the reservoir is almost full then the water volume from a large wave is unable to be accommodated and will therefore spill out of the reservoir, a loss of energy. A balance must be struck here.

A computer simulation model was made in 1999 at Aalborg University. This illustrated the operation of the system working with a simple control strategy, variable turbine characteristics, reservoir crest heights and properties in different sea states. During the Wave Dragon development programme further work was conducted at the Technical University of Munich, and Aalborg University further refining the model, to include turbine start-stop losses and more intricate control methods. This has allowed a comparable turbine control strategy to be used on the Wave Dragon prototype in Nissum Bredning.

Through knowledge of the future overtopping events the turbine control strategy can be modified to improve the efficiency. The possible effect is quantified by modifying the simulation programme to include complete knowledge of the next few waves. This enables a different control algorithm to be designed, including parameters according to the accuracy and time length of the prediction. In physical reality this would be implemented by measuring the wave a distance ahead of the overtopping ramp and extrapolating to the future waves at the ramp with the use of a digital filter. The inaccuracies caused by non-linear waves and spreading will be accounted for to give a confidence in the prediction. Testing of the wave prediction and control strategy will be conducted on the Nissum Bredning prototype.

Overtopping

From work conducted in connection Wave Dragon project (Martinelli and Frigaard 1999, also Hald and Frigaard 2001) a relation for average overtopping for the Wave Dragon has been made.

$Q^* = 0.025\exp(-40R^*)$	Overtopping Relationship
$Q^* = \dfrac{\overline{Q}\sqrt{s_{op}/2\pi}}{b\sqrt{gH_S^3}}$	Non-dimensional average overtopping flow
$R^* = \dfrac{R_C}{H_S}\sqrt{\dfrac{s_{op}}{2\pi}}$	Non-dimensional crest freeboard
$\overline{Q}$	Average overtopping flow
H_S	Significant wave height
b	Breadth of ramp
$s_{op} = H_S / L_{op}$	Wave steepness
$L_{op} = \frac{g}{2\pi} T_P^2$	Deep water wave length
T_P	Peak period
R_C	Mean value of crest freeboard relative to MWL

However overtopping events are a random process with a broad spread. Kofoed and Burcharth 2000 validated a model of the overtopping time series as a Weibull distributed function for each wave. Firstly the probability of overtopping is given for a wave as a function of H_S and R_C with a shape factor c = 1.21.

$$P_{ov} = \exp\left\{-\left(c\frac{H_S}{R_C}\right)^{-2}\right\}$$

If overtopping occurs the probability P_V of overtopping greater than a given volume V_W is:

$$P_V = P(V \geq V_W) = \exp\left\{-\left(\frac{V_W P_{ov}}{\overline{Q}T_M}\right)^{0.75}\right\}$$

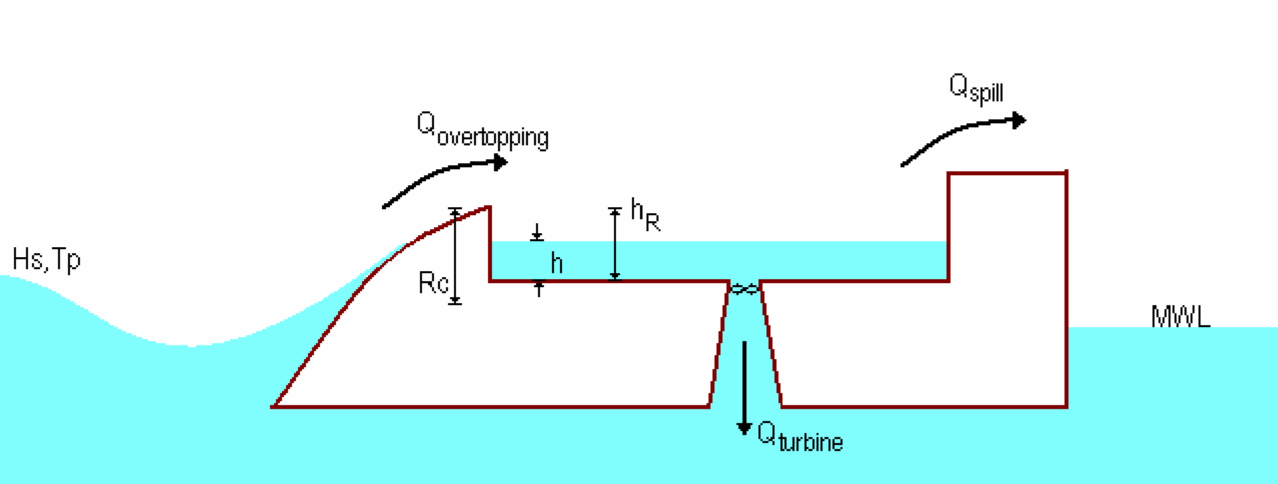
The hydraulic energy of the water overtopping the ramp into the reservoir is a function of the crest freeboard. This can be expressed as average power over the reservoir, and this can be used to define an optimum crest freeboard to maximise the hydraulic power overtopping into the reservoir.

$$PowerIn = g\rho_{water}\overline{Q}R_c$$

$$R_c(Optimum) = \frac{H_S}{40}\sqrt{\frac{2\pi}{s_{op}}}$$

However there are several stages to be overcome after the water has passed over the crest, before this energy is converted into electricity. It is necessary to consider the whole system including reservoir, turbines, generators and electrical conversion equipment to find the optimal crest freeboard for electricity production.

Efficiency



Schematic of flows on Wave Dragon

The figure above shows the inflows and outflows for a Wave Dragon. Mass balance enforces:

$$Q_{Turbine} = Q_{Overtopping} - Q_{Spill}$$

The hydraulic power through the turbines is:

$$P_{TurbineHydraulic} = g\rho_{water} Q_{Turbine}(R_C + h - h_R)$$

Comparing this with the power overtopping the ramp gives:

$$\eta_{Hydraulic} = \frac{Q_{Turbine}(R_C + h - h_R)}{Q_{overtopping} R_C} = 1 - \frac{h_R - h}{R_C} - \frac{Q_{Spill}(R_C + h - h_R)}{Q_{overtopping} R_C}$$

To maximise this hydraulic efficiency it is desirable to:

1. Ensure the reservoir is close to being full, energy is lost if the overtopping flow drops after passing the crest.
2. Prevent too much volume spilling from the reservoir.

As the overtopping flow is very unsteady, it is impossible to fully satisfy both of these cases. Control of the turbine flow allows a balance to be struck here.

The crest freeboard for a floating structure will change, with the Wave Dragon the area of the reservoir is approximately 70% of the platform area, a change in the water level of the reservoir by 10cm will change the freeboard by 7cm. This is an unfavourable effect, there will be more water overtopping when the ramp is in a low position, when the reservoir is full and so more likely for spill to occur. In the higher position when it is desired to fill the reservoir there will be less overtopping. Therefore the changes in reservoir level should be kept to a minimum by the control of the turbines.

The efficiency of the turbines in converting the hydraulic energy is dependent on the turbine type, the hydraulic head and the speed of the turbine rotor. From the simulation work already performed (Knapp 2000, and 2001) the choice of many (16-24) small variable speed low head Kaplan turbine has been made for the Wave Dragon. These allow good control of the turbine flow, and thus give the best energy production. A larger reservoir has several benefits. As a larger volume can be accommodated by a small change in reservoir level, it is possible to keep the reservoir closer to being full and vary its level less.

Simulation

In wave basin scale it is impossible to model the control of turbines. Therefore the majority of the work on the turbine control strategy has been conducted using computer simulation. Below is a brief chronology of the work done to date. The precise control algorithms are not detailed for reasons of intellectual property.

The targets of the optimisation are to achieve maximum conversion efficiency, uniform power delivery and high load factor. All of the following simulation routines have also been used to study the influence of the following parameters on the Wave Dragon optimisation in a given sea state.

- Crest freeboard height
- Turbine number, size and characteristic
- Minimum reservoir level

The sea states used are the standard wave height distribution for the Danish part of the North Sea.

Stockholm 1999: *Holmen*	As a first approach, the operation of 16 turbines is modelled using an overtopping time history derived from measurements on the Wave Dragon model in the wave basin.
Aalborg 1999: *Jakobsen and Frigaard*	The original simulation programme models the overtopping as random individual events in line with the overtopping measurements made on the model. The simple turbine model includes efficiency and flow based on hydraulic head for a number of identical turbines. The crest level is variable dependant on reservoir water level. The turbines are controlled dependant on the reservoir water level. This programme has a nice graphical interface showing the time history of the events.
Munich 2000: *Knapp*	This model aimed to more accurately model the time history to thus optimise the control strategy and turbine choice. The time steps are shorter than a wavelength and more realistic turbine losses are modelled. The control algorithm is configured by defining set levels of the reservoir water level to start and stop individual or grouped turbines. The batch control of the programme enables optimization of a large range of parameters. It was used to verify turbine choice and to define optimum combinations of crest freeboard and turbine control strategy for a number of different wave states.
Aalborg 2000: *Madsen and Frigaard*	This simulation builds on the earlier model by including turbine losses of volume and energy at start-up dependent on hydraulic head. Many runs of the simulation were made to investigate the effect of the same simple control strategy in different sea states. The overtopping model made for this was verified in the paper Kofoed and Burcharth 2000. This was also used for more considerations regarding the optimum crest free board (Hald and Friis-Madsen 2001)
Munich 2001: *Knapp*	The updated version includes a realistic modelling of the energy losses occurring during start-up and shut-down of the turbines. A revised study of the optimum operating parameters was performed.

WD Nissum Bredning 2003, 2004

For 20 months in 2003/2004 the 1:4.5 scale prototype Wave Dragon in Nissum Bredning has been operating with a full control system written by Wave Dragon project partner Baslev ApS. A long time-span (slow) control strategy is used to match the crest freeboard to the measured sea state (Hs, Tp). This is implemented by blowing compressed air into open buoyancy compartments.

The turbine control strategy is again based on reservoir water depth. A similar hysteresis effect as in the Munich simulations is incorporated as the choice of turbines to be active is configurable. In reality measurement is harder to be made with obvious unknowns such as overtopping and spill flow, also a level of uncertainty in the reservoir depth. However the flow through the turbines is calculated and electrical power at all stages is measured.

Prediction

In the Nissum Bredning prototype Wave Dragon the waves are measured by a pressure sensor approximately 50m ahead of the ramp. This length of two to three wavelengths clearly gives some possibility for knowledge of the incoming waves, and thus probable overtopping. Potentially from this knowledge the energy capture of the device may be improved. In a full scale Wave Dragon this wave analysis could be performed on a buoy ahead of the Wave Dragon, or perhaps on some part of the mooring.

To transfer the waves from the measurement point to the ramp a digital filter is to be used. Water waves are dispersive, with different frequency components travelling at different velocities. The filter would have the following form in the frequency domain.

$A(\omega) = 1$ Constant amplitude as there is no loss of energy

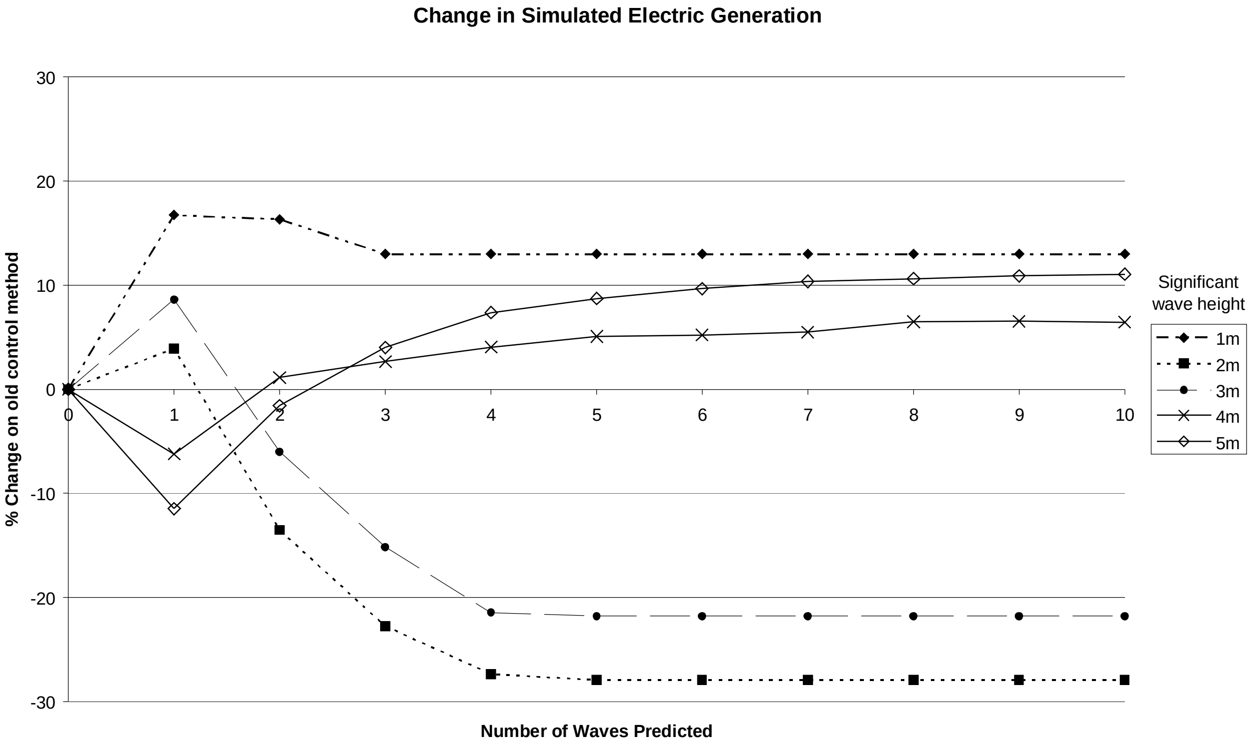
$\varphi(\omega) = \dfrac{-V_p(\omega)}{D_M}$ Phase shift, depends on phase velocity and distance to measurement point

$V_p(\omega) = \dfrac{g}{\omega}\tanh\left(\dfrac{2\pi h}{L}\right)$ In the intermediate depths that Wave Dragon is likely to be sited in neither Deep Water approximations nor Shallow Water approximations may be made, therefore the phase velocity is a function of the frequency, water depth and wavelength. This approach which is assuming linear oblique irregular waves is based on the paper Frigaard and Brorsen 1995. To improve this filter the effects of directionality and higher order wave effects must be included.

To convert a prediction of waves at the ramp to a prediction of the overtopping over the ramp is not straight forward. It is intended to test the prediction algorithm on the prototype by measuring run-up with a capacitance gauge on the ramp and the Wave Dragon in a high floating position. Overtopping volume can be correlated to run-up on a structure, which is easier to measure.

Control using Prediction

In order to evaluate the possible benefit of a turbine control which is based on overtopping prediction, this type of control strategy has been implemented into a simulation programme based on the work conducted in Aalborg between 1999 and 2001. As a first approach, the predictive algorithm is based solely on the knowledge of a future number of waves.



The above figure shows the increase in captured energy over a theoretical hour where a given number of waves are predicted. In the largest sea state (Hs = 4, 5 m) there is between 7 and 10 % additional energy absorbed. In the lower sea states (Hs = 2, 3 m) there is actually a large drop in captured energy. This effect is due to poor tuning of the control system and the crest freeboard height, so that often the reservoir is almost fully empty.

From these results an initial estimate for a position of the wave recording can be made. Here it is clear that in larger sea states more prediction is needed before results converge. For example in the Hs 5m sea state, captured energy is down for predictions of 1 and 2 waves ahead, this is as the control strategy attempts to keep the reservoir almost totally full, and so there is a greater spillage loss. When five or more waves are known there is good convergence. Returning to the problem of real-world wave prediction accuracy will decrease with length of prediction. Therefore an optimum balance needs to be found.

The increases shown here with this crude programme are small. However the capital cost of this is tiny so even a single percent increase in generation is worth while. Further studies combining all the aspects mentioned in this paper will be performed.

Conclusions and Further Work

There is considerable work to be conducted on the wave prediction side of things. In addition to uncertainties due to the usual non-linearities and directionality the shape of the Wave Dragon itself will have an influence. The simpler numerical models must be tested on the Nissum Bredning prototype to understand how well the overtopping can be predicted. This may lead to more a more complex method of overtopping prediction.

The initial study into the potential benefits of knowledge of the future overtopping events gave a potential improvement in the energy capture of up to 10 %. This is a very good result which shows this work to be well worth conducting, the costs of improved control are negligible so this is ‘free energy’ to be captured. Research will proceed by optimising the computer simulations and testing improved strategies on the Nissum Bredning prototype.

Bibliography

Falnes J. 2002 “Ocean Waves and Oscillating Systems”, Cambridge University Press.

Frigaard P. and Brorsen M. September 1994: “A time-domain method for separating incident and reflected irregular waves”, Coastal Engineering 24 (1995) 205-215

Hald T. and Frigaard P. May 2000: “Strategy for Regulating the WD Free Board”, Hydraulics and Coastal Engineering Laboratory, Aalborg University.

Hald T. and Frigaard P. November 2001: “Forces and overtopping on 2. generation Wave Dragon for Nissum Bredning”, Hydraulics and Coastal Engineering Laboratory, Aalborg University.

Hald T. and Friis-Madsen E. March 2001: “Strategy for regulating the crest free board of a floating wave energy converter”, MAREC 2001.

Holmén, E. November 1999: "Report on simulations of the behaviour of turbine units and storage basin level for four turbine layouts", VeteranKraft AB, Stockholm

Knapp W. February 2000: “Report from a parameter study concerning the layout, design and operation strategy of the water turbines to be employed in the Wave Dragon”, Lehrstuhl für Hydraulische Mashchinen, TU München.

Knapp W., Holmén E. and Schilling R. December 2000: “Considerations for Water Turbines to be used in Wave Energy Converters”, Proceedings of the 4th European Wave Energy Conference.

Knapp W. March 2001: “Report from a parameter study concerning the energy losses during start-up and shutdown of the turbines in the Wave Dragon”, Lehrstuhl für Hydraulische Mashchinen, TU München.

Kofoed J. P. and Burcharth H. F. December 2000: “Experimental verification of an empirical model for time variation of overtopping discharge”, Proceedings of the 4th European Wave Energy Conference.

Jakobsen K. P. and Frigaard P. November 1999: “User’s Manual for the Program Wave Dragon – Power Simulation”, Hydraulics and Coastal Engineering Laboratory, Aalborg University.

Jakobsen J. and Kofoed J. P. September 2005: “Wave Dragon Buoyancy Regulation Study”, Hydraulics and Coastal Engineering Laboratory, Aalborg University.

Madsen J. B. and Frigaard P. September 2000: “The Wave Dragon: Operating Strategy of the Turbines”, Hydraulics and Coastal Engineering Laboratory, Aalborg University.

Martinelli L. and Frigaard P. May 1999: “The Wave Dragon: 3D overtopping tests on a floating model”, Hydraulics and Coastal Engineering Laboratory, Aalborg University.