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Influence of buoyancy control performance on power production by the Wave Dragon Nissum Bredning Prototype

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ABSTRACT

This paper reports on the real sea performance of the buoyancy control system of Wave Dragon, a floating wave energy converter using the overtopping principle. The device operates with the full independent control system which has been tested during three years of operation. The impact of the buoyancy control system performance on the power production is noted. This provides motivation and a target for improved control algorithms.

KEY WORDS: Wave energy converter, Wave Dragon, Active control, Power production, Sea testing.

INTRODUCTION

There is very little literature published on control strategies used in the real sea on Wave Energy Converters (WECs) and results from long term testing of such. This paper will present the Wave Dragon (WD) device, explain the first generations control strategy used onboard the prototype for the last 3 years of real sea testing and present detailed results from this period.

The WD is a WEC utilizing the overtopping principle. The structure consists of a floating platform with an integrated reservoir and a ramp, as illustrated in Fig. 1. Waves overtop the ramp and enter the reservoir. Here the water is temporarily stored before it is led back to the sea via hydro turbines generating power to the grid, using the head in the reservoir. The platform is equipped with two reflectors focusing the incoming waves towards the ramp, which enhance the power production capability.

A 237 tonne prototype of the WD has been grid connected and undergoing sea trials in Nissum Bredning, Denmark, since Spring 2003. A thorough introduction to the prototype testing is given by Kofoed et al. (2006).

The floating platform of the WD has open bottom chambers as a part of its structure. By controlling the air pressure inside these chambers, the floating level, the heel (the quasi static inclination of the platform along the centre line - wave induced oscillations are filtered out) and trim (the quasi static inclination of the platform perpendicular to the centre line) of the platform are actively controlled. In order to maximize the power production the desired floating level set-point are altered to fit the prevailing wave conditions. The prototype experience has shown that performing active control of the buoyancy automatically in real time is far from trivial. This paper will discuss dependency between the power production and the performance of this active buoyancy control.

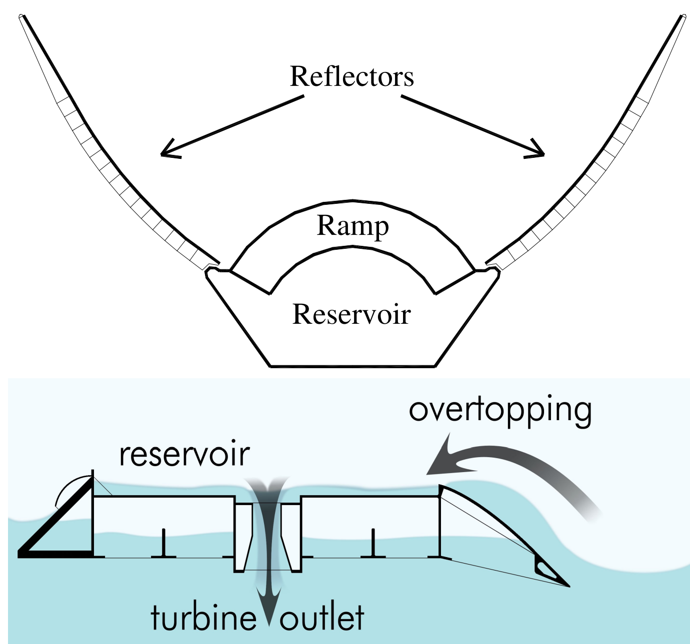

Fig. 1. Above: Main components of the WD. Below: The basic principle of the WD, 1) waves overtopping a ramp, 2) water stored in a reservoir above sea level and 3) water discharged through hydro turbines.

Fig. 2. Above: WD prototype at test site in Nissum Bredning. Below: WD prototype in heavy wave conditions.

Pictures from the prototype installation in Nissum Bredning are shown in Fig. 2. The conclusion of the years of experience and extensive testing of the prototype device in terms of energy absorption and power production is that the performance lives up to the expectations previously deducted from laboratory tests and numerical simulations of the device. The power production is dependant on a well behaving buoyancy control system.

Control strategies

The control strategies applied to a WEC are crucial for the power production performance. Given the physical control equipment, improving control algorithms is very valuable, for no extra capital or maintenance cost it will improve the performance of a device, and give free extra energy capture. Therefore, a major focus of the currently performed research is put on this topic. Without any active control the WD is designed to withstand the most extreme storms, the control acts to improve the performance.

On the basic scale, as with several other WECs WD has two control loops. A slow acting control loop is used to tune the device to the current sea state. A much faster acting control strategy is used to extract the maximum energy from wave to wave or groups of waves.

The main aim of the slowly acting control is to regulate the floating height of the WD to the optimal level for the current sea state. This aims to maximize the power flowing over the ramp. A lower floating level will have more flow but at a lower head, and a higher floating level will have lower flow but a higher head – the optimum must be found.

The time scale of the change in sea states is of the order of a few hours. Therefore, the platform can also change its buoyancy, and thus floating level, at a similar rate. The input to this control strategy is the current, or future, sea state which can be measured directly in the region of the WD, or predicted based on weather forecasts.

Fig. 3. WD prototype seen from beneath at launch in March 2003. The open air-chambers are used to control the floating level.

Simultaneously, the heel and trim of the platform also need to be maintained as close to a preset value (normally zero) as possible. Due to the layout and non constant cross sections of the air chambers, and the free surface water volume in the reservoir, there is dependence between several buoyancy parameters.

The method for controlling the floating level, heel and trim of the platform is by blowing air into, or venting air from, open compartments beneath the reservoir. These open compartments can be seen in Fig. 3.

Due to the free surface of the reservoir this can be compared to balancing a tray full of water. The layout of these compartments and the detailed strategy for filling them is crucial to maintain stability. For example if there is a large central compartment filled with air, and low buoyancy at the edges the device will be quite unstable. However, in general the more stable the platform is, the closer to full the reservoir can be, and so the more power will be generated.

The faster acting control is performed to maintain a suitable water level within the reservoir. If the water level is too high, then large waves will not be able to be accommodated in the reservoir so there will be considerable spill from it. However, if the water level is lower the head across the turbines is less so less power can be produced from the same water overtopping the ramp. Again an optimal compromise must be found.

Controlling the reservoir level is done by turning the low head turbines on and off in a cascade fashion using cylinder gates. At a minimum reservoir set-point the first turbines cut-in, as waves fill the reservoir the remaining turbines progressively start, up to a maximum level where all turbines are operational. The water level in the reservoir can either be determined from pressure transducers within the reservoir itself, or from measurements of the power generated by the generators, from which the head can be inferred.

An area of development here is in the use of predictive algorithms, to control the turbines dependant on the expected overtopping in the next few waves. By lowering the reservoir level when some large waves are approaching, spill would be minimized. Also by maintaining a higher reservoir level when smaller waves are expected, less water would be discharged at a lower head. Initial studies by Tedd et al. (2005) have shown that an increase in performance of 5 to 10 % is possible. (See also Tedd and Frigaard, 2007.)

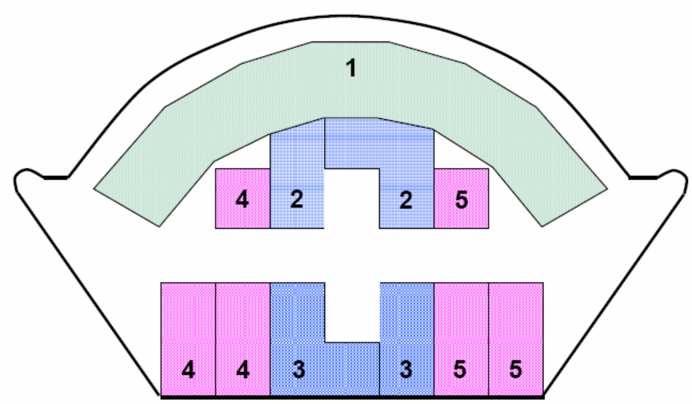

Fig. 4. Schematic layout of the air-compartment zones at the WD prototype.

In the following the influence and importance of specifically the slow acting control, the buoyancy regulation, is investigated. At first, the currently employed buoyancy control algorithms are briefly introduced.

BUOYANCY CONTROL PROCEDURE

As explained the buoyancy control system is designed to keep the platform floating level, as well as the heel and trim at the calculated set-points. These can be constant values or a function of the sea state. This section explains the hardware which is in-place to operate this, and introduces the control algorithm used at the moment.

As shown in Fig. 3 and Fig. 4 the device has a number of open air-compartments. These are joined into 5 zones:

Zone 1:	Beneath the ramp
Zone 2:	In the centre of the platform, the largest group.
Zone 3:	On the centre line to the rear
Zone 4:	To the port side
Zone 5:	To the starboard side

Each of these groups is connected to two valves, one to vent air, and the other connected to a blower, as illustrated in Fig. 5. The valves are operated electrically by the use of a PLC. Pressure transducers beneath the device give the floating level, heel and trim (which are backed up by inclinometers on board). The air-pressure within the chambers is measured; however this is not currently used in the control system and it is not backed up by other readings.

The control algorithm on board has been developed empirically along with the testing of the device. The main criteria have been to have a simple and robust system. This has kept the device working and afloat for three years, and enabled it to respond to the waves. It operates in a sequence as shown below (some details are omitted for intellectual property reasons). NB: PV is short for Process Value and SP is short for SetPoint.

Step 0, No operation:
If Buoyancy = ON and Buoyancy_MAN = Off Goto Step 1

Step 1, Select Trim adjustment:
If Trim_SP < Trim_PV Goto Step 2
If Trim_SP > Trim_PV Goto Step 4
Else Goto Step 7

Step 2, Adjust for light positive Trim:
If compensation successfull Goto Step 6
If step time-out Goto Step 3

Step 3, Adjust for heavy positive Trim:
If compensation successfull Goto Step 6
If step time-out, set alarm for logging and Goto Step 6

Step 4, Adjust for light negative Trim:
If compensation successfull Goto Step 6
If step time-out Goto Step 3

Step 5, Adjust for heavy negative Trim:
If compensation successfull Goto Step 6
If step time-out, set alarm for logging and Goto Step 6

Step 6, Close valves:
If step time-out Goto Step 7

Step 7, Select Heel adjustment:
If Heel_SP < Heel_PV Goto Step 8
If Heel_SP > Heel_PV Goto Step 10
Else Goto Step 13

Step 8, Adjust for light positive Heel:
If compensation successfull Goto Step 12
If step time-out Goto Step 9

Step 9, Adjust for heavy positive Heel:
If compensation successfull Goto Step 12
If step time-out, set alarm for logging and Goto Step 12

Step 10, Adjust for light negative Heel:
If compensation successfull Goto Step 12
If step time-out Goto Step 11

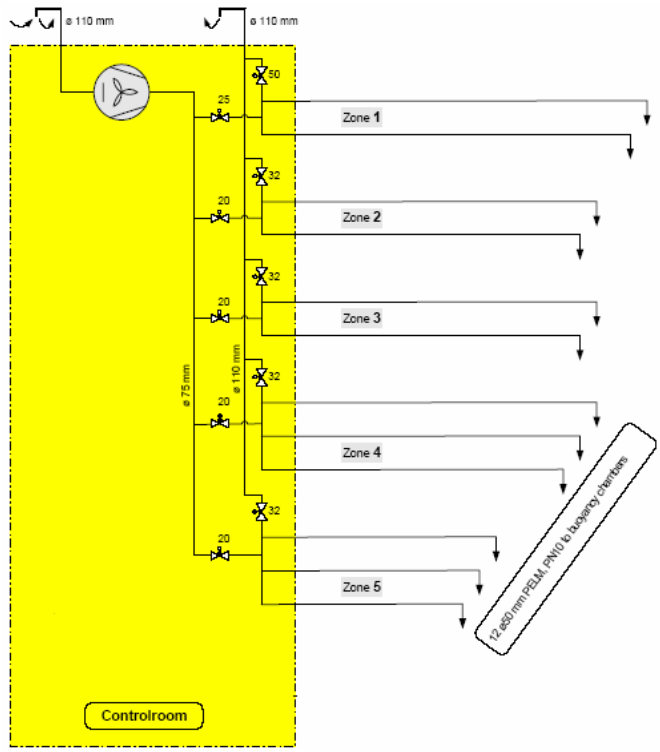

Fig. 5. Schematic layout of the blower and valve system deployed at the WD prototype, which are controlled by the buoyancy regulation system.

Step 11, Adjust for heavy negative Heel:
If compensation successfull Goto Step 12
If step time-out, set alarm for logging and Goto Step 12

Step 12, Close valves:
If step time-out Goto Step 13

Step 13, Select Floating Level adjustment:
If Float_SP < Float_PV Goto Step 14
If Float_SP > Float_PV Goto Step 16
Else Goto Step 1

Step 14, Adjust for too high Floating Level:
If compensation successfull Goto Step 18
If step time-out Goto Step 15

Step 15, Adjust for much too high Floating Level:
If compensation successfull Goto Step 18
If step time-out, set alarm for logging and Goto Step 18

Step 16, Adjust for low Floating Level:
If compensation successfull Goto Step 18
If step time-out Goto Step 17

Step 17, Adjust for much too low Floating Level:
If compensation successfull Goto Step 18
If step time-out, set alarm for logging and Goto Step 18

Step 18, Close valves:
If step time-out Goto Step 1

The difference between "light" and "heavy" corrections performed in the various steps for floating level, heel and trim, lies in how large a part of the air chambers are being used actively in the correction process. Eg. in Step 8 "Adjust for light negative heel" (meaning the front is too low and the rear is too high) the correction could be done by just venting Zone 3, while in Step 9 "Adjust for heavy negative heel" the correction could be done by venting Zone 3 and blowing air into Zone 1. Obviously, a large variety of combinations of actions can be taken to achieve correction for either light or heavy negative heel, as well as for the other steps, and a large number of combinations have been tested in the search for good settings.

There is considerable flexibility for configuration within this system. The system can be configured to perform any action to achieve the compensation (above examples of simple suggested actions are given). The allowable difference between set-points and process values (hysteresis) can be modified. The time to perform a step (the step timeout) can be changed, but has typically been set to values in order of minutes, resulting in typical durations of a total compensation cycle of 20-40 minutes, depending on the need for compensation. During the real sea trials many combinations of settings have been tested and adjusted to obtain better performance.

As it can be seen from the simple actions described above, an action aiming to do one thing may well achieve another. For instance in Step 8 the given compensation will also decrease the floating level.

In addition to the shown sequence, there are some emergency actions. These cause the loop to jump to another action if needed. For example, if while compensating for heel, the trim of the device goes beyond an emergency level, the control will jump to correct this. Other emergency procedures will kick in for other issues, such as a loss of grid connection.

The Wave Dragon has been designed with more than enough closed buoyancy tanks to survive even if all control has failed, and the valves to all of the air chambers are left open. Such a condition has also been tested in periods with harsh weather conditions to prove survivability.

PROTOTYPE DATA

Using data from the period 2004.12.18 – 2005.01.08 a preliminary investigation of the influence of the performance of the buoyancy control system on the ability of the WD to harvest the available wave energy in terms of estimated power, based on flow through the turbines, is performed. During this period reflectors were not attached.

The data has been gathered continuously in half hour records during this time, each sampled at 10 Hz. From the raw data sub series corresponding to the following criteria have been selected:

- $H_s > 0.32$ m
- Volume captured during half hour sample > 10 m^3
- Turbine(s) active at least 20 % of the time.

In Fig. 6 to Fig. 11 plots are shown of efficiency (estimated power based on flow through the turbines / energy in waves arriving at the ramp) as functions of standard deviations and averages of floating level, heel and trim, respectively (all normalized with the significant wave height H_S). Each data point corresponds to a half hour record.

DATA ANALYSIS

As there are many random processes ongoing in the real sea environment it can be hard to separate these and make definite judgements. Therefore the graphs presented have been supplemented by a simple trend line, in order to illustrate the interpretation of the behaviour. The descriptions aim to capture the qualitative nature of this trend, and explain it.

From the graphs in Fig. 6 to Fig. 8 it can be seen that the performance in terms of efficiency is generally decreasing for increasing standard deviation of the parameters floating level, heel and trim, describing the performance of the buoyancy control system. I.e. the better a job the buoyancy control system is doing keeping the platform steady, the better the overall the power capture. The efficiency is also dominated by other factors, such as wave direction, setting of other control parameters for the turbine operation, etc. These give considerable amounts of scatter to this picture. The trend is clearer for the floating level and the heel, which also show the largest excursions.

Considering the average values in Fig. 9 to Fig. 11 it appears that the there is a peak for the relative floating level as expected in the region 0.5 – 1.0. However, the picture is much dominated by scatter. For heel it is worth noticing that the centre of the points does not appear to be right at 0 as generally intended in the buoyancy control. This could be due to a bias inherit in the setting of the buoyancy regulation.

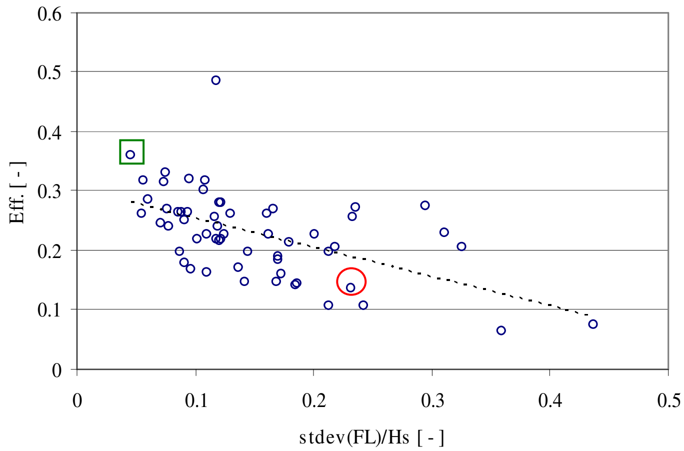

Fig. 6. Efficiency as a function of standard deviation of floating level normalized by significant wave height. A linear best fit line shows the trend.

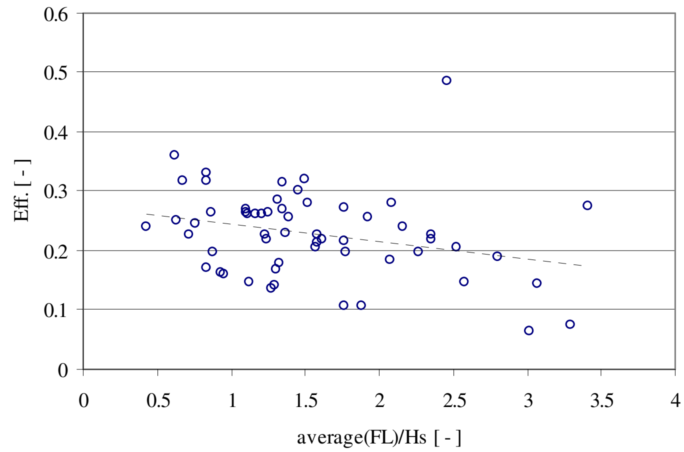

Fig. 9. Efficiency as a function of average of floating level normalized by significant wave height. A linear best fit line shows the trend.

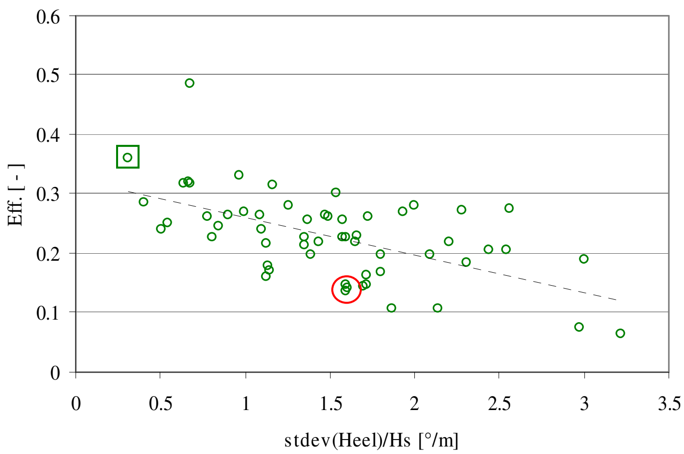

Fig. 7. Efficiency as a function of standard deviation of heel normalized by significant wave height. A linear best fit line shows the trend.

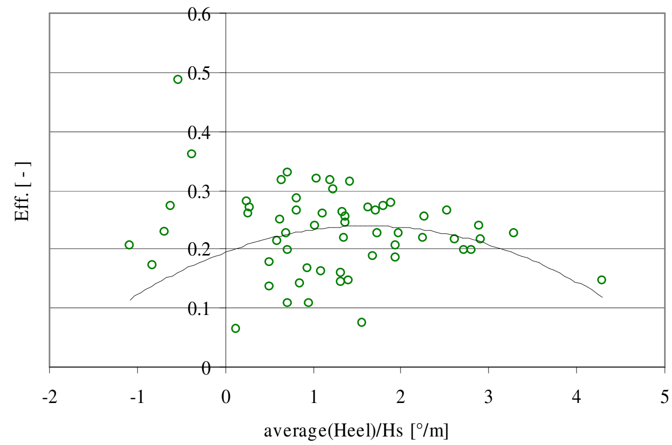

Fig. 10. Efficiency as a function of averages of heel normalized by significant wave height. A quadratic best fit line shows the trend.

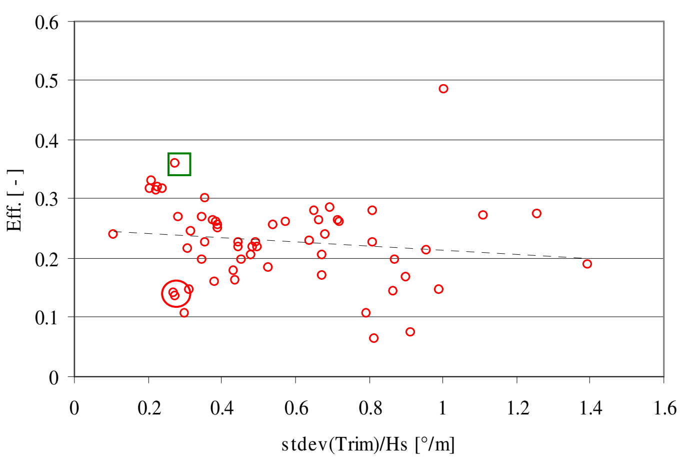

Fig. 8. Efficiency as a function of standard deviation of trim normalized by significant wave height. A Linear best fit line shows the trend.

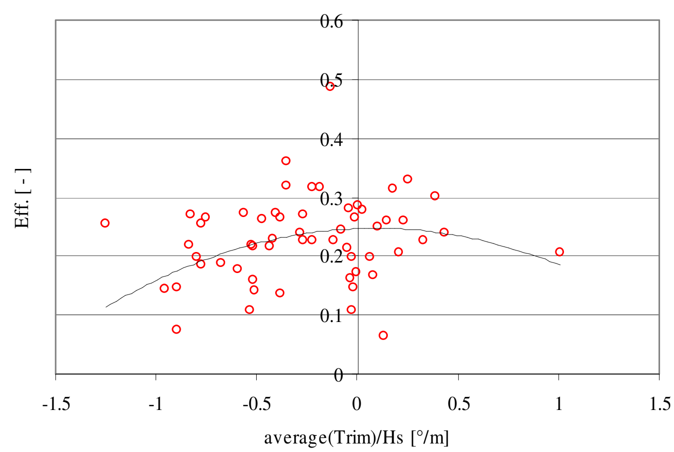

Fig. 11. Efficiency as a function of average of trim normalized by significant wave height. A quadratic best fit line shows the trend.

Table 1. Key parameters characterizing a half hour data record with reasonably good performance of the buoyancy control system (marked with large green circle in Fig. 6 to Fig. 8).

Good			
041230_WD_122.DAT	02-01-2005		03:42
H_S	0.63	m	
HydrPower	1.8	kWh	
FL_stdev	0.029	m	
Heel_stdev	0.20	°	
Trim_stdev	0.17	°	
Eff.	36	%	

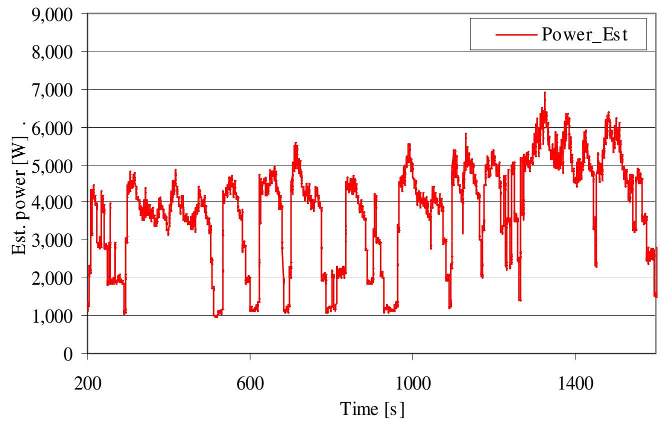

Fig. 12. Half hour time series of estimated power based on flow through the turbines in a case where floating level, heel and trim, are reasonably well controlled by the buoyancy control system.

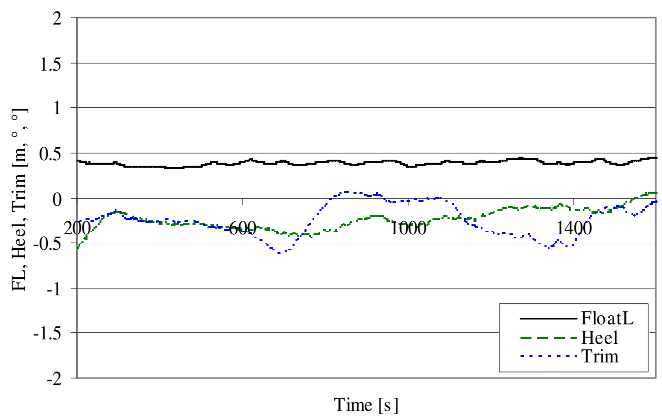

Fig. 13. Half hour time series of floating level, heel and trim corresponding to the above figure, where the buoyancy control system is performing reasonably well.

Table 2. Key parameters characterizing a half hour data record with poor performance of the buoyancy control system. (marked with large red circle in Fig. 6 to Fig. 8)

Bad			
041220_WD_84.DAT	22-12-2004		08:59
H_S	0.96	m	
HydrPower	2.3	kWh	
FL_stdev	0.13	m	
Heel_stdev	0.89	°	
Trim_stdev	0.15	°	
Eff.	14	%	

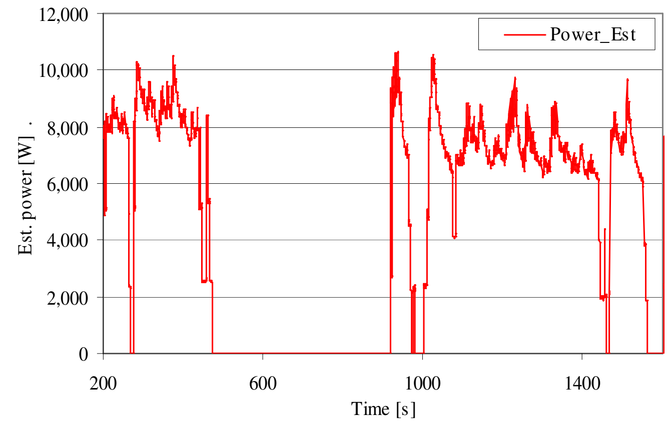

Fig. 14. Half hour time series of estimated power based on flow through the turbines in a case where floating level, heel and trim, are relatively poorly controlled by the buoyancy control system.

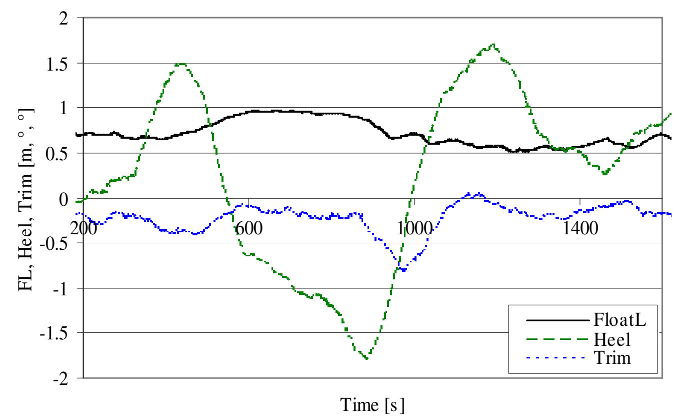

Fig. 15. Half hour time series of floating level, heel and trim corresponding to the above figure, where the buoyancy control system is performing poorly.

In Table 2 and Fig. 14 to Fig. 15 key parameters and examples of a time series representing a half hour record, with relatively poor performance of the buoyancy control system, are shown in more detail. These data correspond to one point (marked with larger red circle) in Fig. 6 to Fig. 8.

In Table 1 and Fig. 12 to Fig. 13 key parameters and examples of a time series representing a half hour record, with good performance of the buoyancy control system, are shown in more detail. These data correspond to one point (marked with green square) in Fig. 6 to Fig. 8.

Table 3. An explanation of the key parameters given in Table 1 and Table 2:

Filename	Date Start Time
H_S	Significant wave height as measured by a pressure transducer mounted to the mooring pile
HydrPower	Power in water passing through the turbines.
FL_stdev	Standard deviation in floating level.
Heel_stdev	Standard deviation in trim.
Trim_stdev	Standard deviation in trim.
Eff.	Ratio between HydrPower and incident wave energy.

From these two data sets it is seen that there is a periodicity in the buoyancy control. This is most pronounced in the case with poor buoyancy control performance for heel, but it is also the case for trim in both cases. This is also the general experience from the daily operation of the device. This periodicity is tightly linked to the sequential characteristics of the buoyancy control system.

Comparing these two cases it is found that the difference in power production relative to incident wave power (efficiency) is as large as a factor of roughly 2.5. This large difference is not entirely due to the poor performance of the buoyancy control system, but also due to difference in wind (and thereby also wave) direction which, in the shown case of poor performance of the buoyancy control system, is not well aligned with the orientation of the device. However, as illustrated below the effect of poor performance of the buoyancy control system is very noticeable.

When looking at Fig. 14 and Fig. 15 it is seen that especially the large excursions in heel hamper the power production severely. In this typical case what happens is that an attempt to make a small correction to the floating level leads to an unwanted large excursion in heel (positive, meaning leaning to the back). This is then overcompensated by the buoyancy control, leading to large negative heel. Since negative heel corresponds to the platform leaning forward (lowering the ramp) it leads to spilling of water in the reservoir, and thereby loss of total volume of water in the reservoir, this also leads to a higher floating level and thereby less overtopping. As a result no power is produced until the buoyancy system is able to correct this large negative heel and too high floating level. But again the system overcompensates, resulting in another large positive heel peak.

The current buoyancy control procedure is not capable of controlling the floating level, heel or trim individually without influencing the others. The job of the control system is not made easier by the physical design of the reservoir and air chambers. A significant negative influence on the control is the fact that the centre of gravity of the platform is not aligned with the centre of gravity of the water in the reservoir (when heel and trim = 0). This effects the attempts by the control system to compensate for changing water level in the reservoir. This behaviour has been recognized also earlier in prototype testing, and serious attempts to fix this by "patching" the buoyancy control procedure, e.g. by introducing artificial set-points and fine tuning the parameters controlling these and other parts of the control procedures have been made. These efforts have greatly enhanced the performance of the buoyancy control system. However it has not solved the problem entirely and a new approach to the problem is necessary.

There was no dedicated study of the buoyancy control system prior to the prototype testing, as the focus for the WD project has been to gain real sea experiences. Now after evaluating the prototype experience a good point for a thorough study on the buoyancy regulation has been reached.

FURTHER WORK

A buoyancy model of the WD is being developed. This is not trivial due to the complex geometry; free surface water in the reservoir, and also in the open compartments; interaction with the floating reflectors; and the external mooring, wind and wave forces. However, once a model have been established, it will be possible to calibrate it through tests on-board the prototype. With such a model more complex Multiple-Input-Multiple-Output (MIMO), State Space, Fuzzy Logic, or other advanced control concepts can be applied and tested.

Once the best control concept has been identified, through thorough testing using the buoyancy model of the WD, as well as the WD prototype, this concept will be implemented into the control system of full-scale power production versions of the WD, which are planned to be built at various locations in the European part of the Atlantic Sea.

CONCLUSIONS

The testing of the Wave Dragon prototype has shown it capable of producing the power levels expected. The paper has illustrated how the power production of the Wave Dragon prototype tested during three years of operation in real sea conditions is quite sensitive to the performance of buoyancy control system.

The first generation buoyancy control system, using a stepwise simple feedback loop logic, developed and used in the prototype testing has shown a non-optimal performance in a considerable part of its operation time, which results in a reduction of the power production of the device during these time periods by factor of up to more than two. This has motivated ongoing research aiming at improving the regulation strategy and thereby ensuring better overall power production capabilities.

ACKNOWLEDGEMENTS

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FURTHER INFORMATION

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

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