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PILOT MODEL TESTS ON THE 'GREEN WATER CONCEPT' FOR WAVE ENERGY CONVERSION WITH MODEL SCALE POWER TAKE OFF (PTO) MODELLING

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ABSTRACT

This paper presents the pilot model tests on the 'Green Water Concept' for wave energy conversion. These tests also included the initial modelling of an electric and hydraulic Power Take Off (PTO). The accurate modelling of a PTO is an important aspect in testing of wave energy conversion concepts numerically and in a wave tank: at the moment that energy is converted into electricity in the PTO, the hydrodynamic behaviour of the structure is changing.
The present tests confirmed the high motions and large amount of green water of the Green Water Concept as predicted in previous simulations. The application of a real PTO gave important insight in the possibilities and challenges of PTO modelling at model scale. For the present concept a mean Power (at full scale) close to 1MW was generated in a regular wave of H=3.0m for the maximum possible setting in the chosen test set-up. This setting was limited by the chosen mechanical and electronic motor set-up in this pilot test series, not the actual maximum of the Green Water Concept itself. Considering the test results, it is clear that the potential of the system is significantly larger.

BACKGROUND

Wave energy is a concentrated form of wind energy: the wind transfers energy into the waves over a long fetch. Cruz [1] has estimated that Europe has an average wave power of 50kW per metre width of wave front [1]. Others [2] indicate that worldwide the economically exploitable amount of wave energy is estimated at 2,000 TWh/year, an average power of 200GW over a year. This is equivalent of 200 large power stations. The challenge is to generate a predictable amount of energy, in a reliable way, at a reasonable cost. These challenges of wave energy are very similar to those of the offshore industry: safe and economic design, production, transportation, installation, maintenance, repair and removal. Besides that, knowledge about reducing motions from offshore hydrodynamics can be used by 'inverse engineering' to increase the motions of wave energy converters to maximise the wave energy conversion into useful electrical energy [3-6].

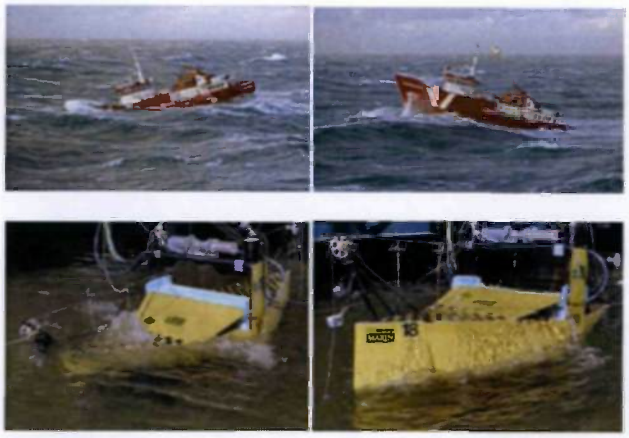

Figure 1: The 'Green Water Concept' uses knowledge about ship motions to develop a wave energy device through 'inverse engineering'

That is why MARIN decided to use its ship and offshore hydrodynamic expertise to assist the development of this type of renewable energy. This resulted in the development of the 'Inverse Concept' or 'Green Water Concept' for wave energy conversion [5]. The concept is a combination of 'heaving' or 'pitching' concepts (making use if the relative motions with respect to the seabed) and 'overtopping' concepts (where the overtopping wave flow is collected in a reservoir and used to generate electricity through a turbine) [7]. Beside the fact that the concept itself might be a feasible wave energy converter, it is also allows the detailed study of several types of wave energy converter systems at once. As MARIN wants to assist the development of all types of wave energy devices and not just develop the Green Water Concept, the development of knowledge is the main driver for this activity.

The Green Water Concept was initially developed using diffraction theory and Volume of Fluid (VOF) simulations, which were reported in [5]. The present paper presents the pilot model tests that were carried out to better understand the physics and the related behaviour of the system. These tests also included the initial modelling of an electrical and hydraulic Power Take Off (PTO). The accurate modelling of a PTO is an important aspect in testing of wave energy conversion concepts numerically and in a wave tank: at the moment that energy is converted into electricity in the PTO, the hydrodynamic behaviour of the structure is changing.

THE GREEN WATER CONCEPT

The 'Green Water Concept' is a weathervaning small freeboard vessel with a water reservoir in centre, see Figure 2. The structure is moored to the seabed with a pre-tensioned wire from the seabed, over two pulleys to a pre-tension weight hanging over the stern. This single point tethered mooring also keeps the structure weathervaning head into the main wave environment. Compared to the concept presented in [5], the pre-tension weight is now hanging over the stern pulley instead of over the pulley at the bow. The advantage of this set-up is that the actual vertical motions of the weight (and resulting accelerations) are small when the structure is pitching: in pure pitch the vertical weight position is almost stationary.

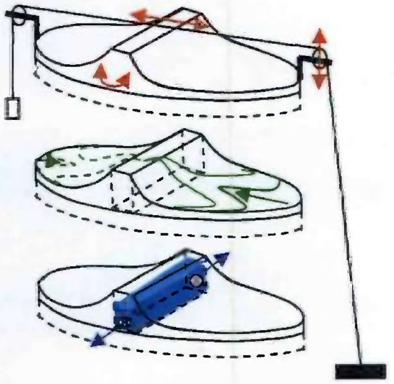

Figure 2: The 'Green water concept' with its three phases of operation

The concept works following 3 steps, as can be seen in Figures 2 and 3:

1. Through maximised pitch motions, the bow makes large vertical motions relative to the seabed, to which it is connected with a wire. The wire moves relative to the structure and can be attached to an electrical generator (first Power Take Off, not in Figure).
2. At the same moment, waves exceed the freeboard and green water flows onto the deck. Green water comes from the front and sides and forms a high velocity water jet. This concentrated jet, together with the upward pitch motions, allows the green water to flow into a higher reservoir at the centre of the structure.
3. The green water in the reservoir then flows back into the sea through low water head turbines (second Power Take Off).

So the concept has two separate ways of Power Take Off. As Figure 3 clearly indicates: the principle of the Green water Concept is a combination of motions relative to the seabed and motions relative to the waves.

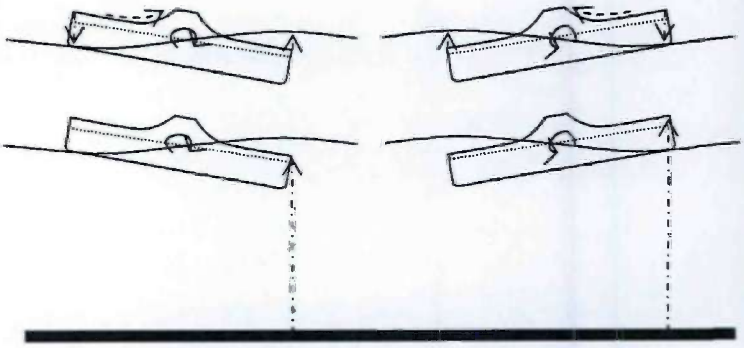

Figure 3: The 'Green Water Concept' uses the relative wave motions and motions relative to the seabed

In [5] it was shown that a 'triangular' (or diamond) type of shape of structure (as shown in Figure 4) has the optimum pitch motions and relative wave motions.

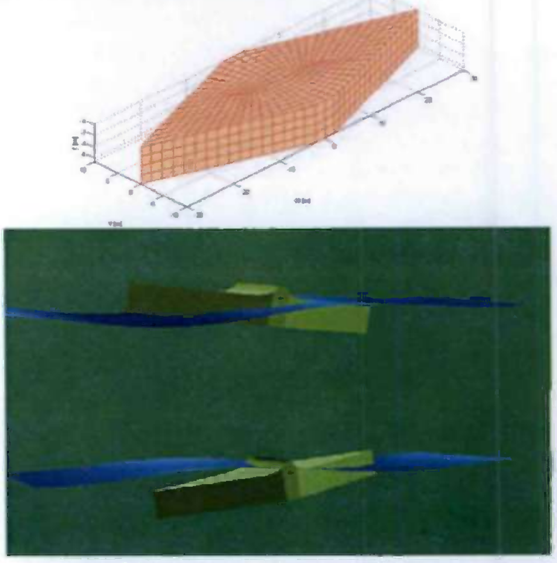

Figure 4: The 'triangular' shape in Diffraction analysis

Figure 5 shows the pitch motion RAO and relative wave motion RAO for a systematic variation of the pitch radius of gyration. A realistic range of kyy was chosen (based on possible water ballast and structural weight): 10m, 12m, 15m, 18m and 20m. This resulted in natural pitch periods of 5.73s-9.29s (1.1-0.68 rad/s). The results in Figure 5 make clear that:

1. The (linear) relative wave motions and pitch motions of the chosen hull shapes are very large
2. The kyy variation allows the tuning of the peak response to the area of maximum wave excitation (and minimum wave damping) and to adjust the Green Water Concept to the period of the incoming waves.

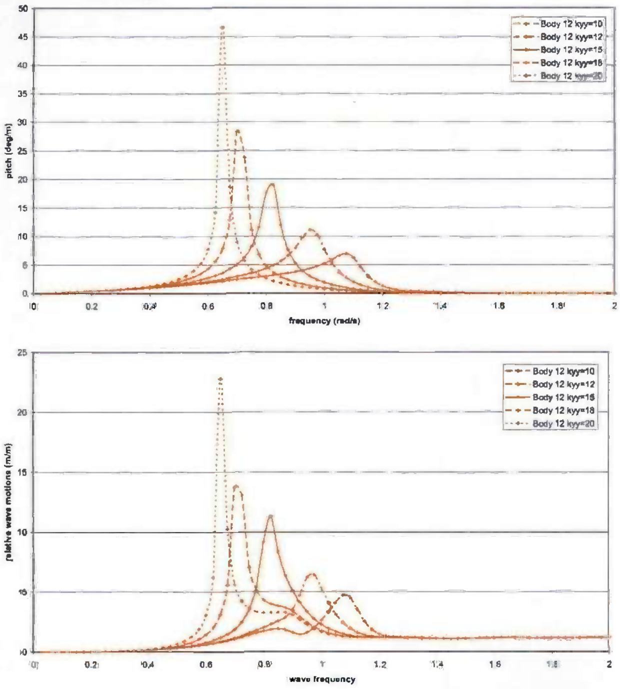

Figure 5 Effect of kyy variation on pitch motions and relative wave motions

The VOF calculations also showed that this shape results in the concentrated high velocity water jet along the length of the structure needed to fill the reservoir in the centre, as can be seen in Figure 6.

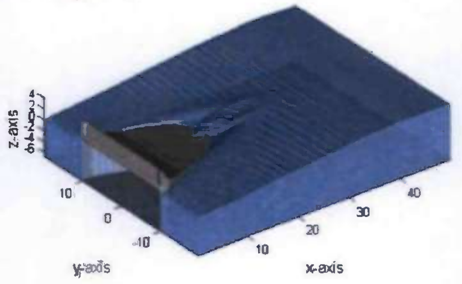

Figure 6: The Volume of Fluid (VOF) simulations [5].

The present pilot model tests are performed to validate these calculations in a situation that is clearly non-linear (with water flowing onto the deck in high waves), to understand the physics and to determine the effect of the Power Take Off (PTO) on the motions.

MODEL, INSTRUMENTATION AND SETUP

For the tests a careful 3D design was made of the model, as can be seen in Figure 7. To have a stiff and watertight model, PVC was used as material. The PVC was welded together and rubber rings were used for removable parts such as decks. Steel and lead ballast weights were used to achieve the correct weight distribution as given in Table 1. The scale was 1:30 and the kyy=16.45m.

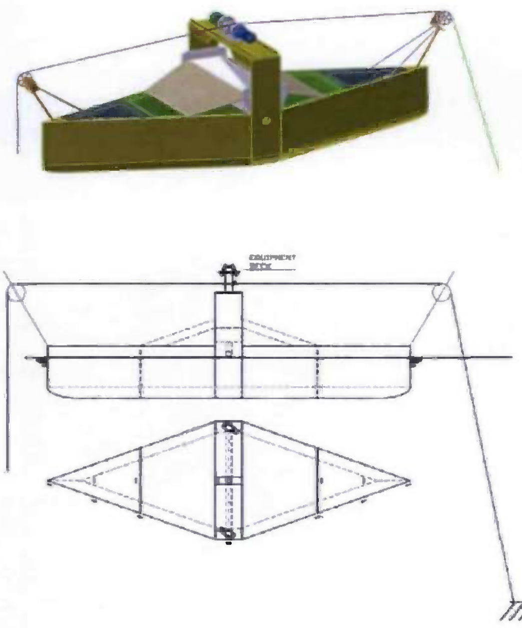

Figure 7: Design of the Green Water Concept model

Designation	Symbol	Unit	Magnitude
Length between perp.	L_{pp}	m	60.0
Beam	B	m	20.0
Depth	D	m	9.0
Draught (even keel)	T_{mean}	m	7.0
Displacement	Δ	tonnes	4628
CoG above base	KG	m	5.21
CoG from station 10	LCG	m	0.0
Transverse GM	GM_T	m	1.11
Transverse radius in air	k_{xx}	m	5.51
Longitudinal radius in air	k_{yy}	m	16.45
Horizontal radius in air	k_{zz}	m	16.45
Pitch period	T_θ	s	8.4
Water depth	WD	m	30

Table 1 Main particulars

Beside this, the following was modelled:

- A streamlined pre-tension weight hanging on the wire at the stern side, consisting of a conical top and bottom with rings in between. The weight could be changed by removing or adding these metal rings (see Figure 11). For the tests 30t to 50t was used.
- Two slopes/ramps were prepared to fill the reservoir: a high ramp up to a level of 4.5m above the deck and a low ramp up to a level of 3.0m.
- The water reservoir had a capacity of approximately 500m^3 (full scale). It was made with downward slopes to the centre to keep the pressure at the bottom high, also with low filling rates (needed for the turbine). The turbine itself was not tested so the tests had either a free outflow or no outflow. The tubes below the deck can be seen on the construction pictures in Figure 8. The outflow rate was approximately 9m^3/s (full scale) with a fully filled reservoir.

Figure 8 Reservoir with outflow on the sides trough a pipe below deck

- Two pulleys at the bow and stern, with force measurement transducers between the pulley and the structure (Fx, Fz).
- To have the Power Take Off (PTO) accessible during the tests, it was placed above the reservoir (in a real situation it would be placed below deck together with the wires). In the next section the PTO modelling will be discussed in detail. At this moment it is important to note that the PTO is a rotating engine/generator with two drums. To prevent a slipping wire on the drum, the wire from the bow side was connected on top side of one drum, whereas the stern wire to the pre-tension weight was connected to the bottom side of the other drum. This can be seen in Figure 10. Two vessel fixed cameras were used on the model for green water flow visualisation on the deck
- The relative wave motions were measured around the structure and the green water height on the deck in front of the ramp, see Figure 7.
- The mooring restoring force (F_x) is a result of the horizontal component of the pre-tension in the mooring wire ($F_{pretension}$). With a horizontal displacement, this horizontal component becomes larger. It can easily be derived that the horizontal stiffness depends on the pre-tension level, water depth (WD) and horizontal displacement according to:

$$F_x = F_{pretension}\cdot\frac{x}{\sqrt{WD^2+x^2}}$$

In Figure 9 the resulting force-displacement curve is given for the 30m water depth with a 300kN pretension.

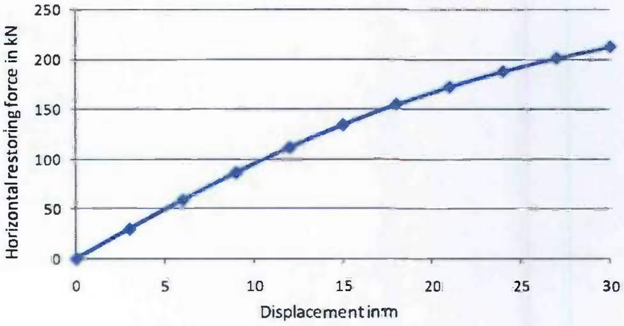

Figure 9 Mooring stiffness with a 300kN pretension in 30m water depth

The final model outside and inside the basin is presented in Figures 10 and 11. Heavy weights at the basin floor were used as bottom anchor.

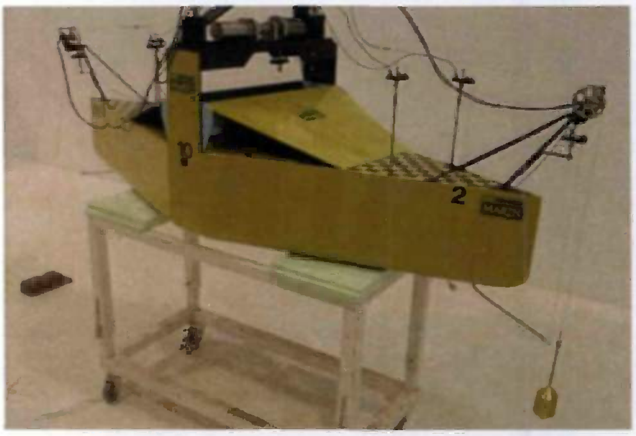

Figure 10 Model with high ramp outside the basin

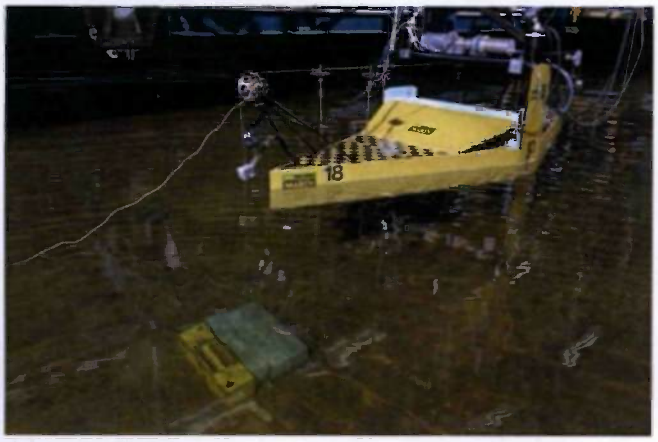

Figure 11 Model with low ramp inside the basin

Careful study of the differences between Figure 10 and 11 shows that the model in the basin has an additional guiding wheel in front of the bow (below the pulley at deck level). This was needed to keep the wire from running off the pulley when transverse motions occurred during the tests.

PTO MODELLING

Function of a Power Take Off (PTO) is to convert kinetic or potential mechanical energy from a structure into electric energy. Important insight in the different PTO concepts in reality can be found in [4, 8-10].

During this conversion forces are exerted by the PTO on the structure. These forces influence the structure's hydrodynamic behaviour. That is why it is important to model the PTO behaviour in numerical and physical testing of wave energy converters. As an initial step in better modelling of PTOs during wave tank tests, the pilot tests on the 'Green Water Concept' also included the modelling of a PTO.

The amount of generated electric power equals the product of delivered voltage and current. The mechanical power needed to drive the PTO is the product of force and speed. By measuring forces and speeds acting on the PTO, the available energy for conversion can be determined in a test setup, independent of specific PTO implementations.

Two main PTO types can be distinquished [8-10]:

1. Constant Speed PTOs. These PTOs are applied in for instance windturbines. When the wind forces increase the RPM of the turbine is not increased but the extra torque (power) is directly dissipated in the grid. Gearboxes are used to match the frequency of the blades with the generator RPM which is determined by the grid frequency. Tidal energy systems like current turbines are suited for this kind of PTO.
2. Irregular Motion PTOs. For application in wave energy converting devices there will be no fixed generator speed. Wave frequency and amplitude will vary causing large time related variations in generated power. To provide a more constant electric flow from the setup to an end user or grid, storage of energy in battery banks or hydraulic accumulators is required.

In the present test the focus will be on application of Irregular Motion PTOs. The structure motions will decrease as a result of the damping forces provided by the PTO. A small damping force will result in limited reduction of motion but also extracts a small amount of power since force is low. An extreme high damping force will result in small motions but also little generated power since speeds are low. Challenge for a PTO control system is to find the optimal and safe working point for maximum power generation for a certain sea state.

During scale model tests, available space and weight are limited and a flexible system is desired to simulate different PTO types and settings. An all electric equivalent is preferred with flexible control of PTO settings. In the remainder of this section, two basic PTO characteristics and a design strategy for model scale PTOs will be described.

Characteristics

For the present tests two types of PTO characteristics were applied:

1. Linear PTO based on a linear relation between speed and generated damping force, just like a viscous friction term often found in mechanic systems. This characteristic is found in direct drive electric generators connected to a fixed resistive load (Figures 12 and 13). The torque T required to turn the generator has a linear relation with the generated current i which in turn is related to the speed in a linear way.
2. Non-linear PTO based on generation of constant damping force for speeds <> 0. This characteristic is found in hydraulic ram based generators (Figures 14 and 15). For motion of the ram a minimal force is required, this force is mainly related to the pressure in the accumulator. A generator coupled to a hydraulic motor can be used to convert the hydraulic energy to electricity at an adjustable constant rate. Peaks in energy conversion are filtered out by the accumulator.

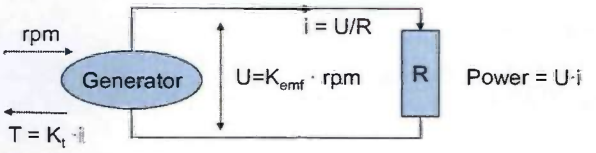

Figure 12 Generator with resistive load

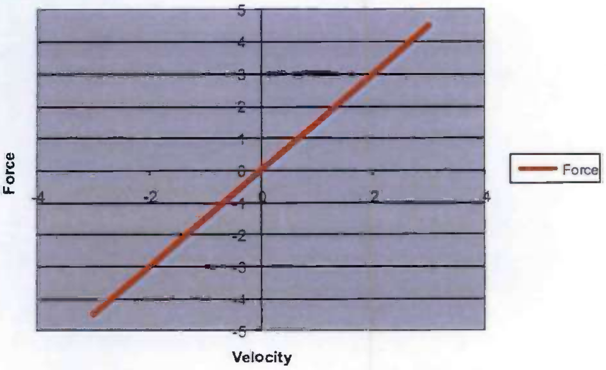

Figure 13 Speed-Force characteristic of linear PTO

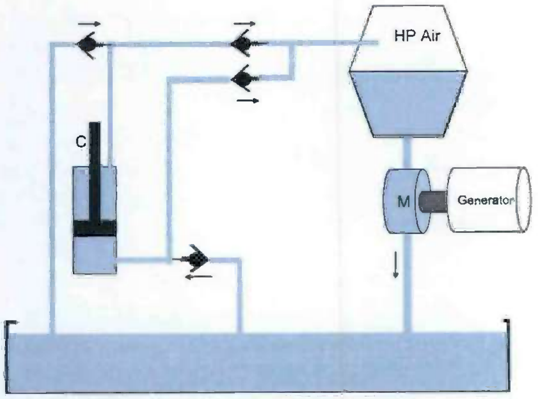

Figure 14 Hydraulic PTO

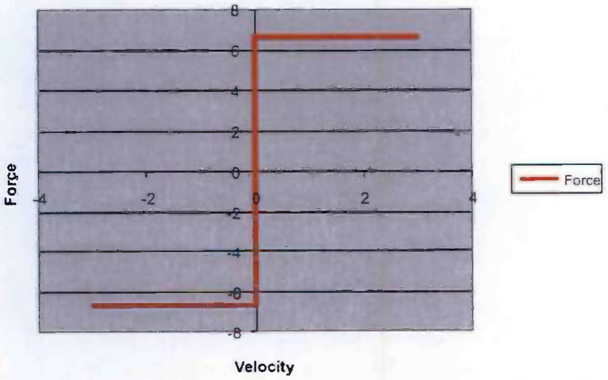

Figure 15 Speed-Force characteristic of hydraulic PTO

Model scale PTO systems

To determine the power generating capabilities of the structure, a model scale PTO must be included in the present tests. Main task of this model scale PTO is to change the structure hydrodynamics in a realistic way and to provide options for measurements of forces and speeds to determine the available power for conversion. For the linear case the application of direct drive small DC motor/generator loaded with a variable resistor seems promising. Unfortunately the relative high winding resistance combined with low generated voltages makes application of these motors unsuitable to test in realistic operating points. These points are characterized by higher torques at low speeds. The application of a gearbox does not improve the situation since it introduces extra stiction and friction terms. These terms are fixed and relative large compared to full scale systems.

For the non-linear, or hydraulic case it is not practical to build a complete hydraulic system with rams, return valves, fluid, accumulator and hydraulic motors coupled to a electric generator. A cheaper but still inflexible approach would be to use pressurized air in the accumulator, water as fluid and a simple adjustable leak from the accumulator.

For the present tests a system was designed to model PTO characteristics using active computer controlled components. Main components of this setup were a direct drive DC electromotor, a digital programmable servodrive and an operator GUI for setting parameters and monitoring the estimated power generation in realtime.

The system was realized by using a velocity mode motor control as shown in Figure 16. In this setup the controller tries to keep the motor RPM at zero rpm by commanding a damping torque from the amplifier connected to the motor. The torque setpoint is proportional by factor K to the actual motor RPM. A limiter (LIM) is used to restrict the maximal realized torque. The motor RPM is measured by differentiating the position information from an incremental optical encoder. Using this electronic approach significant torque can be produced in the electromotor, even at low speeds. By measuring forces, speeds and electric current in the motor, energy conversions can be monitored. The control loop is updated at a rate of 5 kHz.

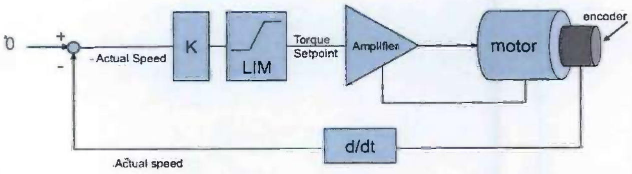

Figure 16 Control system overview for model scale PTO

The motor shaft is connected to a winch to bring an additional force to the pre-tensioned wire of the Green Water Concept model. The relation between the force in the wire and wire speed is shown in Figure 17. The slope of the line is determined by proportional gain K, the maximal produced force by the LIM setting in the controller.

For small K values, the limiter will not be activated and the motor system will behave as linear PTO. When K is increased to a very large value, even at low speeds the limiter will be activated and the behavior will shift towards the non-linear PTO, in this way a hydraulic PTO is modelled in a global way. The influence of changing accumulator pressures is not taken into account in the present tests.

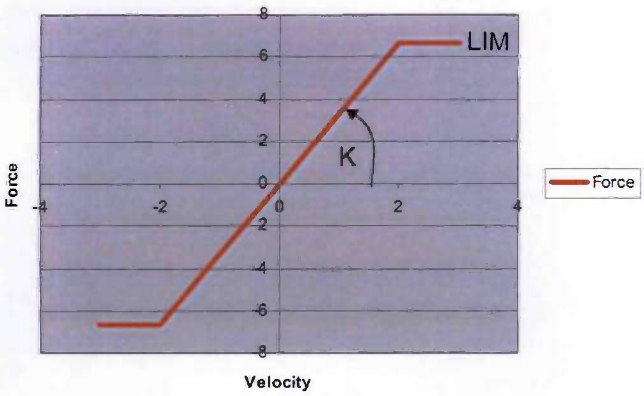

Figure 17 Model scale PTO characteristic

PTO software control

A dedicated PTO control and monitoring software application was designed with functions for:

- Online modification of parameters K and LIM.
- Monitoring of actual electric current and speed of the motor and calculation of electric power from these values and motor K_t.
- Graphical presentation of instantaneous and low-pass filtered generated power for both model scale and full scale.

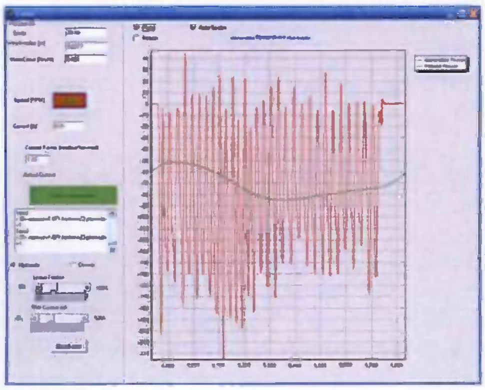

Figure 18 Screenshot of PTO control application

The sofware application also monitors the motions of the motor. For future tests this information can be used to simulate the filling process of a hydraulic accumulator for specific electric load settings. The simulated pressure of the accumulator can directly be used to adjust the LIM value of the control loop. In this way model scale experiments in controlled environments can be coupled to more sophisticated PTO control strategies.

The combination of motor and servodrive can be controlled by PTO control systems provided by suppliers of wave energy concepts. The MARIN measurement system can deliver realtime motion data to 3rd party PTO control systems and accepts force/torque setpoints to be realized by the motor. In this way model scale tests in controlled environments can be combined with testing of full scale PTO control strategies in an early stage of the development process.

The actual application on the Green Water Concept model with motor, drums and encoder on the model and in the design can be see in Figure 19.

Figure 19 Actual application on the Green Water Concept model with motor, drums and encoder on the model

MODEL BASIN AND WAVE CONDITIONS

The MARIN Shallow Water Basin offers a high wave generation capacity in a water depth up to 1.1m. The Shallow Water Basin has horizontal dimensions of 220m (length) and 15.8m (width).

The Shallow Water Basin has a piston type wave maker at the short side of the basin. The opposite side of the basin is equipped with a beach to absorb the wave energy and minimize the wave reflection. The wave maker is equipped with a wave board for generating regular/monochromatic and irregular/random waves. The online computer facilities for wave board control, data acquisition, and data processing allow for direct control and computation of relevant wave characteristics. Wave energy spectra can be prescribed by using standard or non-standard spectral shape or specific of wave trains.

The basin has a translating wave board including 2nd order wave generation technique. This technique corrects for the differences between the oval shaped motions of the water and the linear motion of the wave board, which may cause unwanted free waves in the basin. The second order wave generation takes into account second order effects of the bound first higher and first lowers harmonics of the wave field in the wave board motion. In Figure 20 the design curves of the wave generator at 1m water depth are given. Within these design curves the capacity is only limited by natural wave breaking. Table 2 shows the waves that were used for the actual testing.

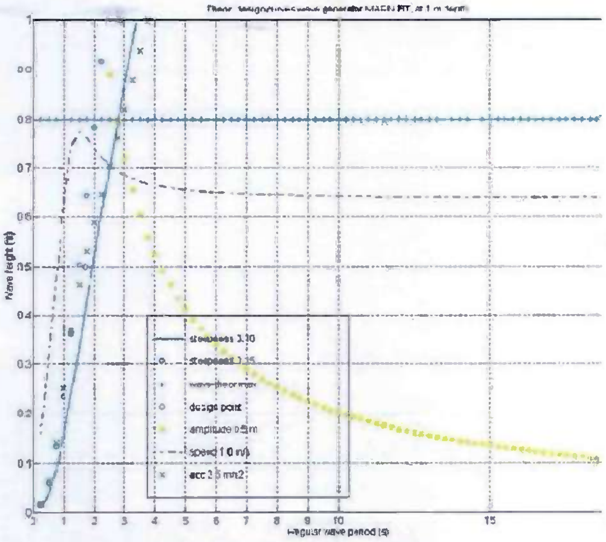

Figure 20 Wave generator capacity

Wave Type	Period (s)	Wave height (m)
Regular	8.5	1
Regular	8.5	2
Regular	8.5	3
JONSWAP 3.3	8.5	1
JONSWAP 3.3	8.5	2
JONSWAP 3.3	8.5	3
JONSWAP 3.3	10.5	3
JONSWAP 3.3	6.5	3

Table 2 Used waves at scale 1:30

OBSERVATIONS

As indicated in the previous section, tests were performed in a series of regular and irregular waves. First tests were carried out without the PTO modelling to better understand the overall hydrodynamic behaviour. These will be presented below. In the next section the effects of the PTO will be described.

The tests confirmed the high pitch motions and relative wave motions in low waves as predicted in [5]. Also the concentrated high velocity water green water jet along the length of the structure (needed to fill the reservoir in the centre) as simulated in Figure 6 was clearly observed.

Figure 21 shows the green water flow onto the deck, this concentrated high velocity jet over the centreline and flow into the reservoir in a regular wave of 3.0m high. Significant amounts of green water reached the reservoir in each oscillation, but it was difficult to quantify these amounts as there was a continuous high outflow at the same moment.

Figure 21 Green water flow onto the deck, concentrated high velocity jet over the centreline and flow into the reservoir

The testing also showed an unexpected behaviour: as sketched in Figure 22, the green water that just did not reach the reservoir resulted in a returning flow on the ramp that impacted on the incoming green water flow of the next wave cycle. This affected the effective flow of green water onto the ramp significantly. This was not identified during the simulations as these considered only one flow event on a fixed structure. This showed the value of the model testing for the evaluation of a concept.

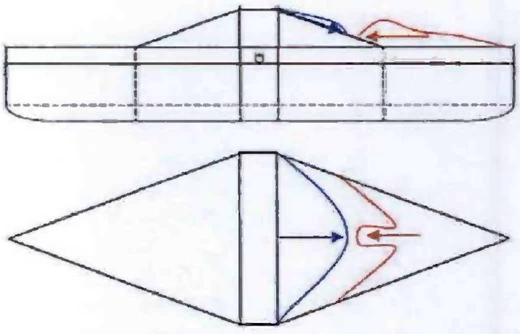

Figure 22 Meeting of incoming flow and returning flow (that just did not reach the reservoir), reducing the effective flow onto the ramp

A possible solution for this problem is an additional ramp level and triangular flow guides below it to guide the returning flow to the sides. This is shown schematically in 23 and will be investigated in future model testing campaigns.

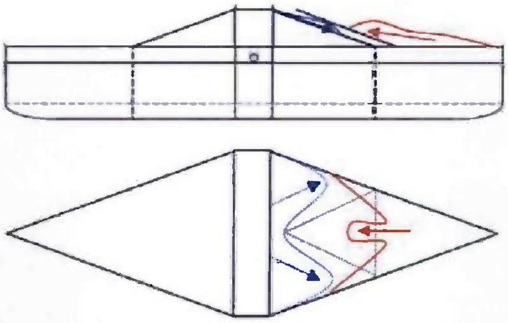

Figure 23 Possible solution with an additional ramp level and triangular flow guides below it to guide the returning flow to the sides

We will now look to the test results in a more quantitative way. Figure 24 shows the time traces in a regular wave of H=3.0m without PTO modelling. The following signals are shown:

PITCH_MOT : Pitch motion
Z_REF : Vertical motion of the forward pulley
REL_FORE1 : Relative wave motion at the bow
REL_RAMP_F : Green water height on the fore ramp
REL_RAMP_A : Green water height on the aft ramp

The following can be observed;

- With a wave height of only 3.0m (~1.5m single amplitude), the single amplitude pitch motion is already 7.6 degrees and the vertical motion at the bow 6.0m.
- There is already approximately 4.5m green water height on centre of the deck in these waves (the freeboard is 2.0m).
- The relative wave motion measurement at the bow is truncated as the wave probe is completely submerged.
- At the stern the relative wave motions and amount of green water on the deck is much smaller. This is confirmed by the comparison between the bow and stern in Figure 25. This aspect needs attention in the further optimisation of the hull in the future.

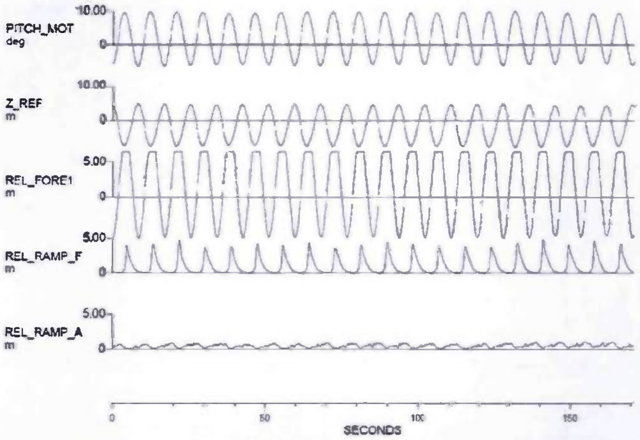

Figure 24 Time traces in a regular wave of H=3.0m without PTO modelling

Figure 25 Difference in green water flow at the bow and stern

Figure 26 shows the Pitch motion RAO in irregular waves (Tp=8.5s) with increasing wave heights of Hs=1, 2 and 3m.

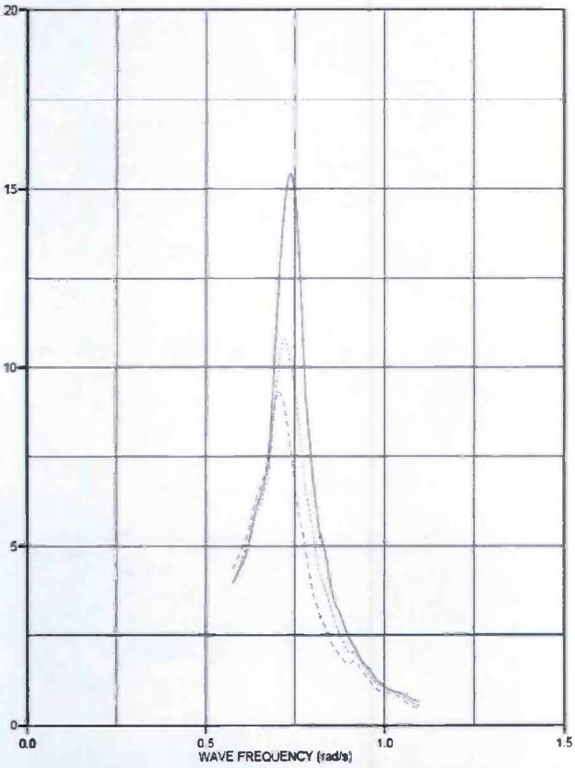

Figure 26 Pitch motion RAO in irregular wave (Tp=8.5s) with Hs=1m (solid), Hs=2m(dotted) and Hs=3m (dashed)

The RAO in low waves of 1.0m (above 15 degrees/m) confirms the predicted very large pitch motions in [5], see Figure 5 (although Figure 5 does not contain the exact kyy value tested). However, the motions are clearly non-linear: the RAOs decrease rapidly with increasing wave height, most probably due to the effect of the green water on the deck. The reduction in the pitch motions can be a measure for (part of) the amount of energy present in the green water on the deck. This needs further investigation in the future.

There were also a few more practical observations, that need careful engineering attention in the future development of the concept:

- The model in the basin needed an additional guiding wheel in front of the bow (below the pulley at deck level) to keep the wire from running off the pulley when transverse motions occurred during the tests.
- There was significant mechanical wear and tear of the wire due to the constant motions over the pulleys. This is a typical wave energy converter problem: instead of reducing the motions as is done in normal offshore engineering, the maximised motions and loads result in a significant wear and tear. Presently less sensitive mooring and PTO driving mechanisms are under investigation as a result.

RESULTS WITH PTO

As a first check of the behaviour of the system with the PTO, pitch decay tests were performed without the PTO and with different PTO settings. Figure 27 shows a typical example for a situation without the PTO and with a 25% PTO setting level of the linear PTO.

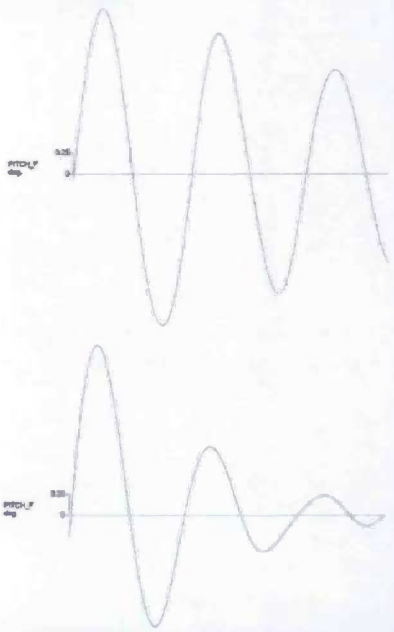

Figure 27 Pitch decay with no PTO (above) and with a 25% PTO setting level, natural pitch period 8.3s

The PTO setting level needs some explanation. Referring to Figure 17, the linear PTO is adjusted with a K damping factor. Based on preliminary tests with the chosen (motor and control) set-up, a maximum K factor was determined before the electronic system became instable. This was set as Kmax. The present tests were done with PTO settings which are certain percentages of this Kmax. So a PTO setting of 25% is 25% of Kmax, not a formal 25% of a critical damping or something similar. In practice the 25% PTO setting was about the maximum possible during the actual testing, as with higher settings slack wire events occurred in the system. Table 3 gives an overview of the decay tests and PTO settings tested.

Testno	PTO setting	δ	b_0/Bc in %
301006	0, disconnected	-0.23	3.7%
301010	1%	-0.57	9.1%
301011	5%	-0.64	10.2%
301012	10%	-0.76	12.1%
301013	15%	-1.13	18.0%
301015	25%	-1.09	17.3%

Table 3 Damping values for different PTO settings

For systems with linear damping only, the logarithmic decrement is constant and its value can be determined using the following equation.

$$\delta = \frac{\ln \theta_i - \ln \theta_{i+N}}{N}$$

In which:

N = number of oscillations, [-]
θ_i = motion amplitude of i-th oscillation
θ_{i+N} = motion amplitude of (i+N)-th oscillation

Based on this the achieved percentage of the critical pitch damping can be derived as follows:

$$\beta = \frac{b_\theta}{B_{critical}} = \frac{-\delta}{2\pi}$$

With:

b_θ = linear damping coefficient, [kNms/m]
$B_{critical}$ = critical damping, [kNms/m]
δ = logarithmic decrement, [-].

The results can be found in Table 3. A clear increase of the percentage of critical damping is observed with increasing K setting. It should be noted that the number of oscillations reduces significantly with higher damping settings (see Figure 27), which makes the damping estimate less accurate. Although the damping increases, the maximum $b_\theta/B_{critical}$ values are all below 20%, so far away from a critically damped system. This implies that the potential of the system to generate electrical energy from the waves (when control and mechanical challenges can be solved) is actually larger than presented below.

The next step was to test the PTO system in actual wave conditions. In the present stage of the project, this was limited to regular wave conditions.

One of the challenges appeared to be to derive the actual derived Power from the tests. Two alternative routes were followed (see Figure 28):

- Derive the Power from the product of Force F (F_TOT in the time traces) in the wire and the velocity of the wire u (VEL_LINE in the time traces). This is refered to as 'POWER':

  $$\text{POWER} = F \cdot u$$

  The problem of this approach was that the force in the line was, due to practical limitations, only measured between the forward pulley and the basin floor (see F_TOT in Figure 28). So this included friction losses in the pulley and guiding system. Further this measurement could not be used to quantify the Power in the part of the motion cycle where the wire load was getting slack sometimes when large PTO settings were used (bow moving down). For this part of the cycle a wire force measurement at the stern side would be needed.

- As a result, an alternative derivation of the Power appeared to be more accurate for the higher PTO settings. This is refered to as 'POW_E' in time traces and is determined on the electronically recorded signal of Torque (T) and rotational motion (ϕ) and speed as follows:

  $$\text{POW\_E} = T \cdot \dot{\phi}$$

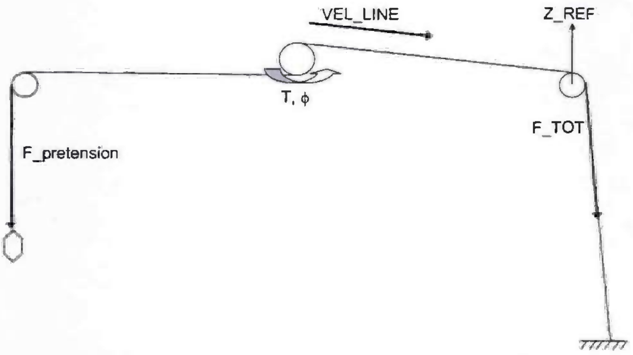

Figure 28 Definition of Power calculation parameters

Figure 29 and 30 give examples of the time traces with the linear PTO in a regular wave of H=3.0m with K settings of 4% and 20% of Kmax.

It can be observed that POWER and POW_E are very close for the smaller K setting, but that the differences become larger for the high setting of 20%. The reason for this is also clear from the time traces: F_TOT becomes zero (slack) is part of the cycle. While the bow moves down, F_pretension should keep the wire under tension. However, with higher PTO settings this pre-tension load is counteracted by the Torque in the PTO.

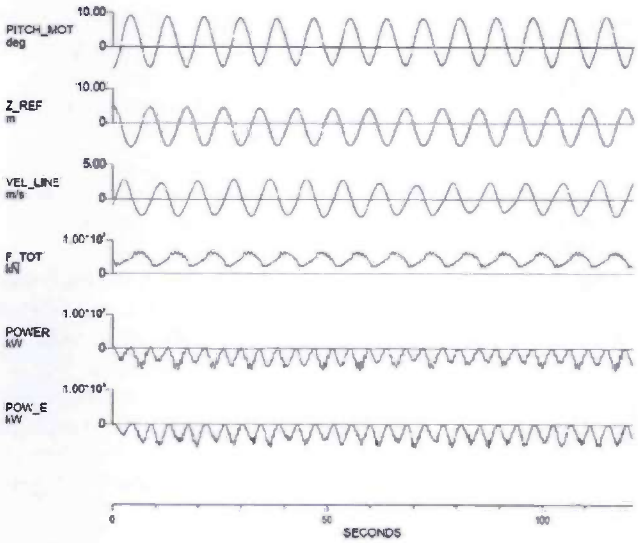

Figure 29 Time traces with a linear PTO (setting 4%) in a regular wave of H=3.0m

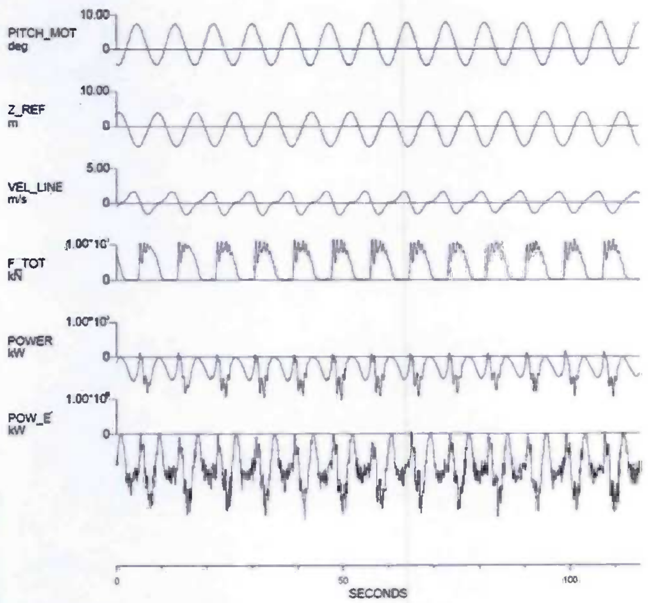

Figure 30 Time traces with a linear PTO (setting 20%) in a regular wave of H=3.0m

Figure 31 shows the mean Power (at full scale) that was generated in the regular wave of H=3.0m. The Figure presents the Power as function of the linear PTO setting (% of Kmax) as indicated above. The Figure shows that the mean generated Power increases almost linearly with the % of Kmax. The maximum mean Power generated is close to 1MW for the 20% setting. It should be noted that this maximum 20% setting was limited by the chosen mechanical and electronic motor set-up for the present pilot tests, not the actual maximum of the Green Water Concept itself: the damping is far from the critical damping (Table 3) and although the pitch and vertical bow motions decrease with increasing PTO setting (Figure 31) as expected, this reduction is not dramatic. So the Green Water Concept is not a resonance-dominated concept where the response (and Power) drops rapidly as soon as electric energy is taken from it. This implies that the potential of the Green Water Concept system to generate electrical energy from the waves (when control and mechanical challenges can be solved) is actually much larger than the already significant 1MW presently achieved. It should ofcourse be noted that a too high damping force will result in small motions and in little generated power since speeds are low. Challenge for a PTO control system is to find the optimal and safe working point for maximum power generation for a certain sea state.

The next set of tests was carried out with the Hydraulic PTO. For the Hydraulic PTO the LIM setting for the Torque (Figure 17) was varied with a maximum motor current setting between 200 and 1500mA (model scale). Figure 33 shows the time trace of the tests with a 1500mA setting.

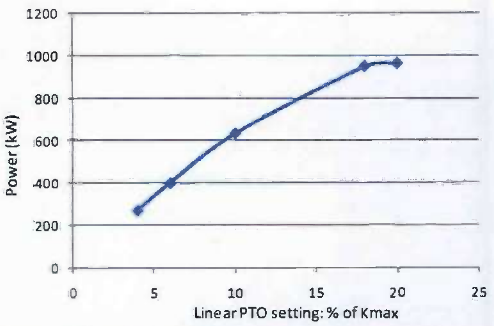

Figure 31 Power at full scale as function of linear PTO setting

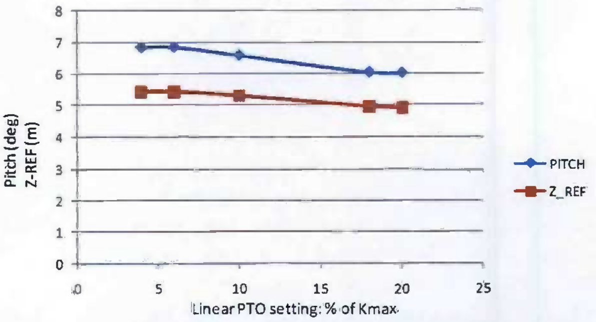

Figure 32 Pitch and Z_REF (vertical motion at bow) amplitude as function of linear PTO setting

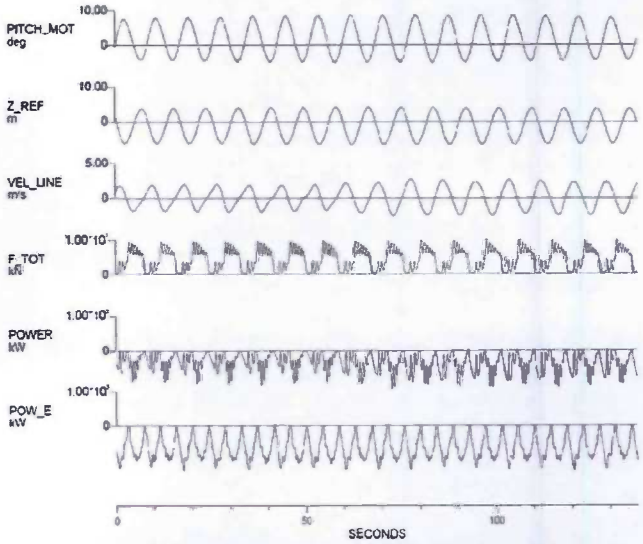

Figure 33 Time traces with a hydraulic PTO (setting 1500mA) in a regular wave of H=3.0m

Due to the fact that this setting is rather assymmetric (PTO load changes with a step each time that the velocity changes sign (not as gradually as in the linear PTO), the dynamics in the line (F_TOT) are larger and some resonant motions can be observed on top of the wave frequency oscillations. In real PTO systems this type of impulsive dynamics need special consideration in the control, as well as in the maximum and fatigue load analysis.

Figure 34 shows the effect of the hydraulic PTO settings on the generated mean Power (full scale). Again this is a preliminary investigation on sensitivities, not the absolute maximum that can be generated with the Green Water Concept.

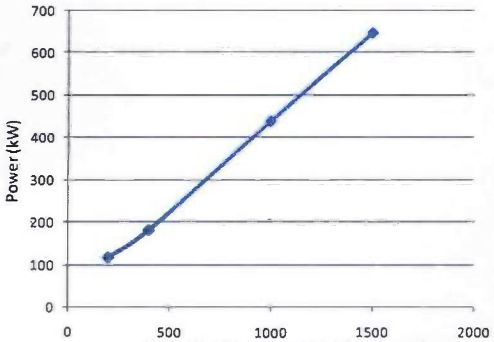

Figure 34 Power at full scale as function of hydraulic PTO setting LIM (Max current)

CONCLUSIONS

Based on the test results presented in this paper, the following conclusions seem justified:

- The tests confirmed the high pitch motions and relative wave motions in low waves as predicted in the simulations. Also the concentrated high velocity green water jet along the length of the structure (needed to fill the reservoir in the centre) was clearly observed. With a wave height of only 3.0m (~1.5m single amplitude), there is already approximately 4.5m green water height on centre of the deck.
- The motions are clearly non-linear: the pitch motion RAOs decrease rapidly with increasing wave height, most probably due to the effect of the green water on the deck.
- The green water that just did not reach the reservoir resulted in a returning flow on the ramp that impacted on the incoming green water flow of the next wave cycle. This affected the effective flow of green water onto the ramp significantly. This was not identified during the simulations as these considered only one flow event on a fixed structure. This showed the value of the model testing for the evaluation of a concept. There are options to solve this problem, like a double ramp.
- The accurate modelling of a PTO is an important aspect in testing of wave energy conversion concepts numerically and in a wave tank: at the moment that energy is converted into electricity in the PTO, the hydrodynamic behaviour of the structure is changing.
- For the present test set-up the Power derived based on the generator torque and rotational speed was more reliable than the power based on the load in the mooring wire as this is influenced a lot by friction losses in the pulley and guiding system.
- The mean Power (at full scale) that is generated in a regular wave of H=3.0m increases almost linearly with the linear PTO setting (% of the maximum realistic damping factor Kmax). The maximum mean Power generated in this regular wave of 3.0m is close to 1MW for the 20% setting.
- This setting was limited by the chosen mechanical and electronic motor set-up for the present pilot tests and is not the actual maximum of the Green Water Concept itself: the damping is far from the critical damping and although the pitch and vertical bow motions decrease with increasing PTO setting, this reduction is not dramatic. So the Green Water Concept is not a resonance-dominated concept where the response (and Power) drops rapidly as soon as electric energy is taken from it. This implies that the potential of the Green Water Concept system to generate electrical energy from the waves (when control and mechanical challenges can be solved) is actually much larger than the already significant 1MW presently achieved.
- A hydraulic PTO is rather asymmetric as the PTO load changes with a step each time that the velocity changes sign (not as gradually as in the linear PTO). As a result the dynamics in the line are larger and some resonant motions can be observed on top of the wave frequency oscillations. In real PTO systems this type of impulsive dynamics need special consideration in the control, as well as in the maximum and fatigue load analysis.

As a next step in the further development of the Green Water Concept, the optimisation of the Power generation based on an optimized Power Take Off (PTO) will be studied based on important insights as can be found [4, 8-10]. This will also be developed numerically in time domain simulation programs. Also the further optimisation of the hull shape and the Power generating capacity of the green water on the deck and in the reservoir will be studied. Finally future PTO investigations should ofcourse focus on the irregular wave response as well.

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