The Ocean Harvester – Modelling, Simulation and Experimental Validation

M. Sidenmark[1], A. Josefsson[2], A. Berghuvud[2], G. Broman[2]

[1] Ocean Harvesting Technologies AB
Ö. Köpmansgatan 27, SE-371 32 Karlskrona, Sweden
E-mail: mikael.sidenmark@oceanharvesting.com

[2] Department of Mechanical Engineering,
Blekinge Institute of Technology,
SE-371 79 Karlskrona, Sweden
E-mail: andreas.josefsson@bth.se

Abstract

Among the significant difficulties of developing commercially viable wave power has been survivability in storm conditions and achieving high capacity factors. The oscillating wave motion, constantly changing wave-size, and extreme energy levels during storm conditions often lead to difficulties in reaching high capacity factors, keeping the system complexity down and avoiding over dimensioning.

The Ocean Harvester is based on an innovation addressing these issues. What is unique with this concept is the way a counterweight is used to achieve a limited load on the generator and thereby a levelled power output that can be controlled to match the average level of incoming wave energy. These characteristics enable an exceptionally high capacity factor, excellent survivability and low system complexity, which altogether may lead to low capital- and O&M costs.

This paper presents the working principle of the novel concept and introductory coordinated theoretical and experimental investigations of performance characteristics. Theoretical and experimental results agree very well and further simulations with the verified model using real wave data clearly show the advantage of the proposed concept. A high capacity factor is proven and the design obviously only requires existing types of components, making cost-efficient wave energy conversion feasible.

Keywords: Ocean Harvester, ocean wave energy, mechanical transmission system, landbased testrig

1 Introduction

Wave power has a large potential of becoming a cost-efficient renewable energy source. Preliminary studies indicate that ocean energy can supply a significant part of future energy needs [1]. The high energy density in ocean waves enables a small power plant in relation to the capacity. Furthermore, wave energy is more predictable than for instance wind energy since the waves are built up by the wind during a long period of time and then continues to swell after the wind subsides. This leads to a relatively slower variation in the average energy.

However, the wave energy is difficult to master. The ocean is a tough environment for structures and materials. At direct driven operation (i.e. when the generator is driven directly by the wave's momentary motion) the irregular wave motion makes it difficult to optimize the power plant and to get a high capacity factor.

The common power grid also requires a relatively steady power level and, consequently, the power generation should also for this reason preferably be generated on an even level, to avoid the need of levelling the power in the transmission system, before it is delivered to the power grid. If done in the latter way, transformers and cables must be heavily over-dimensioned in relation to the mean power, and there is a need for costly capacitors to smoothen the power before it reaches the grid connection.

The Ocean Harvester provides a simple and essentially mechanical solution to these issues, which enables an even power outtake that never exceeds the rated power of the generator. This paper focuses on the mechanical transmission used in the novel concept and gives an overview of recent R&D work.

The conceptual design is described in section 2 followed by discussions concerning simulation models and a landbased testrig in section 3. Some preliminary simulation results are then shown in section 4 to further illustrate the performance of the proposed system.

2 Conceptual Design

The working principle of the Ocean Harvester is illustrated in Figure 1. Two drums, a planetary gear and a generator are built in to a buoy. Energy is absorbed

© Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 2009

from the vertical motion (caused by the rising wave) by means of the anchor drum and a mooring line.

Unlike earlier technologies, the Ocean Harvester uses a counterweight in a way that enables a limited and controllable continuous load on the generator. The counterweight line is separated from the mooring line and instead winded around a counterweight drum which is rigidly fixed to the ring gear in a planetary gearbox. The generator is then fixed to the sun gear and the anchor drum is fixed to the planet carrier.

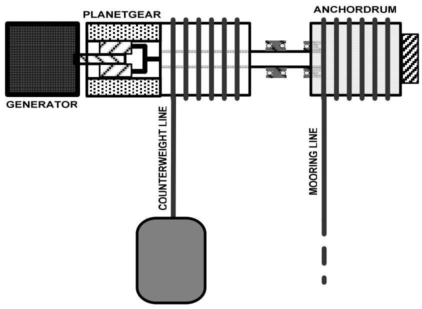

Figure 1: The conceptual design includes an anchor drum connected with two backstop clutches to the carrier in a planetary gearbox. The generator is then connected to the sun gear and a counterweight provides a nearly constant load to the ring gear.

In general, when the wave is rising, the anchor drum is rotated forward, causing the counterweight to be lifted and thereby potential energy to be stored. At the same time the counterweight drives the generator with a limited load that mainly depends on the mass of the counterweight. When the wave sinks, the counterweight continues to drive the generator with maintained load while releasing potential energy.

The energy absorption is accomplished when the anchor drum feeds a driveshaft, which is rigidly fixed to the planet carrier, forward during the rise of the wave. As the wave sinks, the driveshaft is standing still as it is disengaged from the anchor drum. This is achieved with two backstop clutches – one clutch that depends on the relative motion between the anchor drum and the driveshaft and one clutch that is connected between a fixed point in the structure and the driveshaft.

The generator is driven by the counteracting torque (the strength of the electromagnetic coupling in the generator) from the counterweight drum, which depends on the rotation speed, field current and electrical load on the generator and the torque given by the counterweight. The power output can be controlled to match the average level of incoming wave energy by adjusting the field current or the electric load in the generator. If the average incoming wave energy is lower than the energy converted to electricity, the counterweight is moving in a down-going trend while still producing a nearly constant power outtake over the generator. The load is maintained over the generator independently of the actual wave amplitude and only a smaller variation is seen due to inertia effects.

Similarly, when the average incoming wave energy is higher than the energy converted to electricity, the counterweight is moving in an up-going trend. Thus, a controlled power outtake over the generator has been achieved which effectively smoothes out the highly irregular energy from the waves.

In practice a limited accumulation span for the counterweight is available and a control system is needed to make sure that the counterweight stays within a given interval. This is achieved by tuning the counteracting torque from the generator and consequently the power output. The same principle can be used to compensate for the variations due to the inertia effects.

For a relatively calm wave climate the power outtake is kept at a constant less than rated level. As the waves increase in amplitude, it is necessary to increase the power output over the generator. As a result, the counterweight will fall faster and never reach its upper end position. When the maximum rated power has been achieved, the rotation speed cannot be increased any further. At this point the anchor drum is temporarily disengaged from the driveshaft, preventing the generator from being overloaded. However, the counterweight continues to drive the generator on full rated power while falling to a lower position where the anchor drum is again connected to the driveshaft.

3 Modelling and Validation

The system has been studied using both theoretical modelling and prototype testing. Introductory computer simulations facilitated validation of the working principle and motivated further development of the mechanical system. A landbased testrig was then constructed and the simulation models could be verified.

Figure 2 illustrates one of the rigid-body models that have been developed to study the dynamic behaviour. The system is here modelled with backstop elements, elastic lines, inertia in components and a rotational viscous damper as generator. The dynamic equations are formulated with digital filters [2] and realized in MATLAB©, constituting a fast solver with high numerical accuracy. Furthermore, a control system was implemented so that the counterweight position could be controlled by tuning the viscous damping in the model, and disengaging the anchor drum at full buffer capacity.

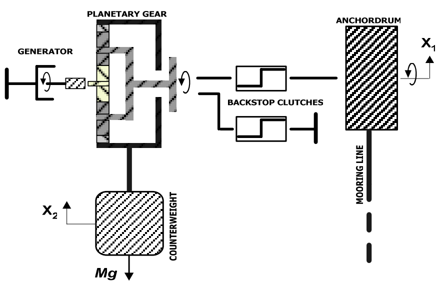

Figure 2: Illustration of a rigid-body model developed to simulate the dynamic behaviour. X_2 is the absolute position of the counterweight and X_1 is the translational motion of the model (the buoy's heave mode).

The land based testrig was further used for practical verification of the working principles and for tests of the mechanical transmission in a controlled environment. The testrig, as shown in Figure 3, consists of a main moving unit (converter) which is lifted and lowered with servo motors. Hence, the same wave signals as used in the simulation models can be tested in the rig. Below the converter is a counterweight which can work in an accumulation interval of around 3.5 m. The fixed wire to the anchor drum can be seen to the right in Figure 3.

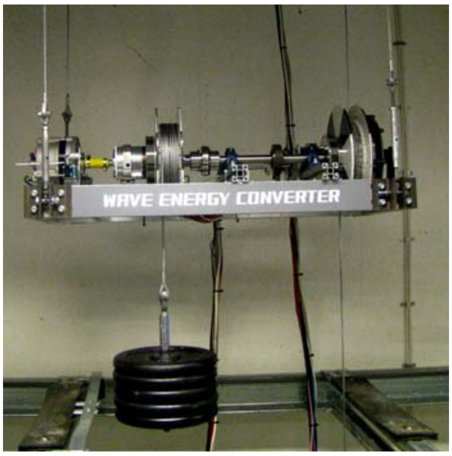

Figure 3: The testrig used to verify the concept and for comparisons with simulation models. The converter is controlled by servomotors so that an incoming wave can be simulated. A counterweight of 50 kg is used in this setup.

A more detailed view of the converter is shown in Figure 4 where two drums, a driveshaft, a planetary gearbox and a generator can be seen. The converter is also equipped with measurement hardware in order to monitor and log rotational speed and position on all rotating components. In addition, an interface to the testrig has been developed where control parameters, such as field winding current and resistive load in the generator, can be controlled.

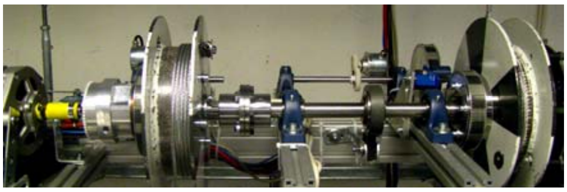

Figure 4: A more detailed view of the converter. The anchor drum can be seen to the right, and the planetary gear and generator to the left.

The simulation model has been updated and verified with the measurement data obtained from the testrig. A series with falltests were first conducted where the converter is standing still and the counterweight is falling while the counteracting torque from the generator is changed. From this data it was possible to identify the rotational inertia in the system as well as identifying the relationship between the viscous damping used in the simulation model and the parameters used to control the power outtake in the experimental setup (resistive load and field winding current).

A typical correlation between the simulation model and the testrig is illustrated in Figures 5 and 6. In this run, the converter is following a sinusoidal signal with constant amplitude and frequency. The field winding current is first kept at a constant level causing the counterweight to move in an up-going trend during its first 50 s. During this time, the generator speed stays at a constant level except for smaller variations due to inertia effects.

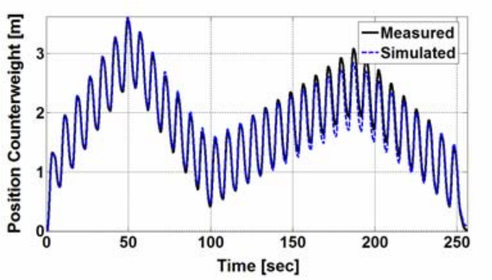

Figure 5: Measured versus simulated position of the counterweight. The converter is moving with a constant amplitude and frequency while the field winding current is changed during the run.

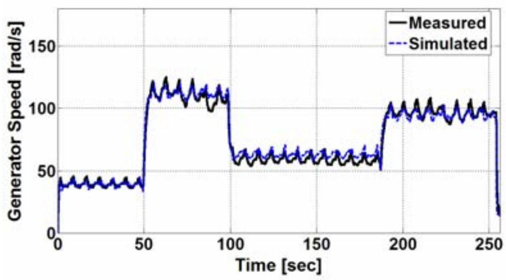

Figure 6: Measured versus simulated generator speed. The converter is moving with a constant amplitude and frequency while the field winding current is changed during the run.

The field current is then suddenly decreased at Time=50 s and a new equilibrium is found in the system with a descending trend for the counterweight and a higher generator speed. Similarly, the field current is increased at 100 s and decreased at 180 s. The position of the converter and the field winding current are used as input signals to the simulation model, and a good match between experimental and simulated results is seen in Figures 5 and Figure 6.

4 Performance Test with Simulation Models

The result from an initial performance test with the simulation model is shown next. The model is rescaled to better fit a planned scale model for sea trials. A counterweight with a mass of 17 ton is used and it is assumed that an accumulation interval of 30 m is available. The generator's rated power is set to 25 kW and a simple control strategy is implemented, as illustrated in Figure 7. The power outtake over the generator is lowered exponentially once the counterweight approaches the bottom and the driveshaft is disengaged from the anchor drum once the counterweight reaches the upper limit.

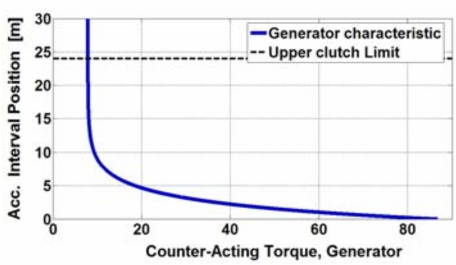

Figure 7: The control strategy used in the simulation. The Power outtake over the generator is lowered once the counterweight approaches the lower limit. A clutch is used to disengage the driveshaft once the counterweight reaches the upper limit.

The wave data selected for this study was measured at Kristianopel, 1991, by Sweden's Meteorological and Hydrological Institute [3]. For each hour, the significant waveheight and mean period is given. A segment of 43 days - from 1991-01-01 to 1991-02-12 - was selected and the daily average can be seen in Figure 8.

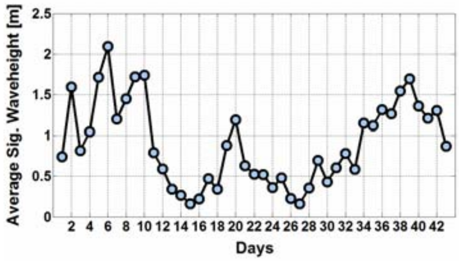

Figure 8: Average significant waveheight from 1991-01-01 to 1991-02-12 (43 days) measured at Kristianopel [3]. The data is originally given for each hour and the average for each day is shown in the figure.

Stochastic time signals are generated to the simulation model, as illustrated in Figure 9. These signals are designed to follow the statistics given by the hour data, i.e. normally distributed around the given significant waveheight and normally distributed around the given mean period for each hour [4]. The wavesignals are then used to create a forced translational motion in the simulation model. In practice, the resulting heave motion of the buoy will be substantially different from the elevation of the incident wave. However, the aim of this study is not to predict the actual level of produced electric power but rather to understand and demonstrate how the mechanical transmission can manage a varying wave climate.

Some detailed simulation results are shown next. Figure 9 illustrates a shorter segment of 70 s, from day 4, where the generated wavedata is shown together with the counterweights position in the accumulation interval. In this case, the counterweight stays around 22 m from the bottom while slowly going in a trend upwards.

The rotational speed of the carrier in the planetary gear can be seen in Figure 10. The driveshaft is rigidly fixed to the planet carrier. Hence, when the wave is lifting, a rotation is transmitted to the planet carrier as can be seen by comparing Figure 9 and Figure 10.

The rotational speed of the sun gear (generator speed) stays relatively constant, nearly independently of the carrier speed as shown in Figure 10.

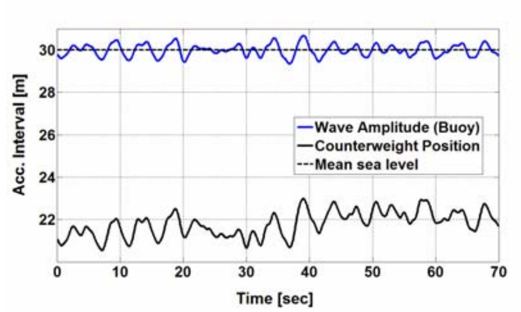

Figure 9: A shorter segment (70 sec) that shows generated wavedata and the counterweights position in the accumulation interval.

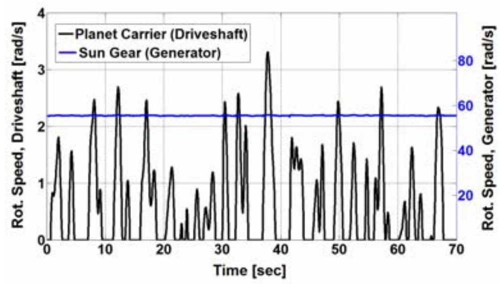

Figure 10: The rotational speed of the driveshaft (left axis) is shown together with the rotational speed of the generator (right axis) for a 70 sec segment. A gear ratio of 100 is used in the simulation.

The counterweights movement in the accumulation interval for day 4 is shown in Figure 11, along with the average counterweight position for each hour. The simulated generator power during the same day is illustrated in Figure 12. The viscous damping in the model is selected so that the generator's rated power (25 kW) will never be exceeded.

As long as the counterweight is above 10 m the power outtake is nearly constant except for smaller variations due to inertia effects. The produced power is varying approximately +/- 4% from its mean value.

As the counterweight falls below 10 m the power outtake is slowly decreased as can be seen between, for example, 3-7 hours in Figure 11 and Figure 12.

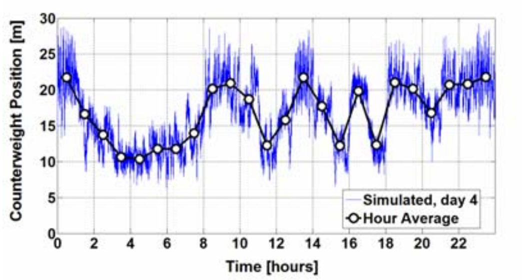

Figure 11: An example of the variation during one day of the counterweight's position in the accumulation interval (30 m). The average position each hour is shown along with the more detailed results obtained from the simulation.

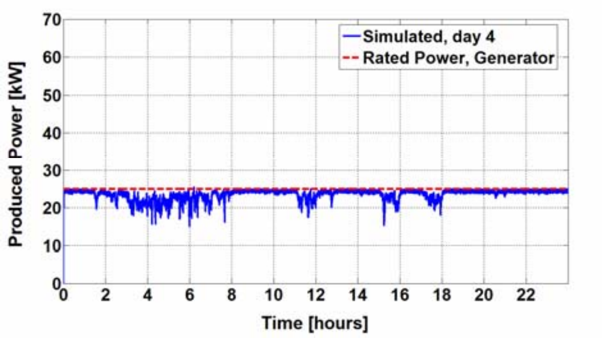

Figure 12: The simulated generator power over one day is shown, together with the generator's rated power (25 kW).

The average power produced over the generator for each day is shown in Figure 13. This can be compared with the average significant waveheight shown in Figure 8. As the wave climate becomes relatively calm between day 12 to 18 and day 24 to 29, the power outtake is decreased below the rated power in order to keep the counterweight above the lower buffer limit.

A nearly constant power outtake is obtained from the powerplant if the wave climate is large enough as is seen between day 2-10 and day 34-42. With a rated power set at 25 kW, the average capacity factor can be calculated for each day as shown in Figure 14. In this simulation, an average capacity factor of 73% was obtained during the 43 days.

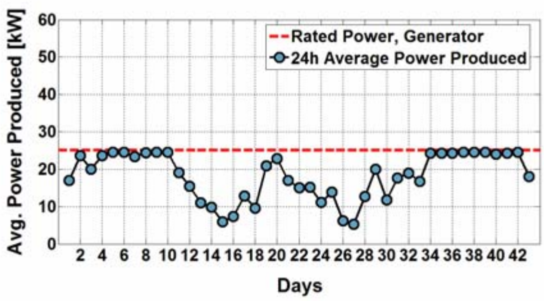

Figure 13. Average daily power outtake during the simulation. The generator's rated power is set to 25 kW.

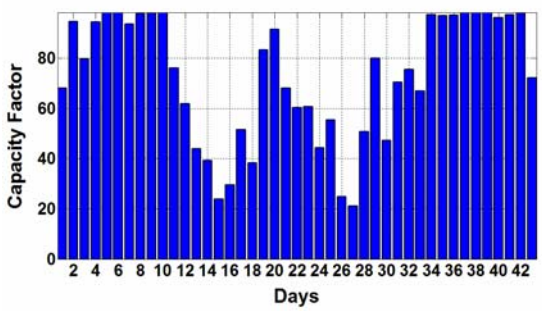

Figure 14. Average daily capacity factor during the simulation. The total average for all 43 days is 73%.

5 Conclusions

This paper presents studies of a novel mechanical transmission in which a counterweight is used to level out the intermittent wave energy absorption. A rigid-body model has been developed to simulate the dynamical behaviour of the proposed mechanical transmission. Furthermore, a landbased testrig has been constructed in parallel to demonstrate the concept and closer examine different configurations in practice. It is shown that the use of the counterweight gives a levelled power output and that the field current on the generator can be used for tuning the power output to match the power in the incoming waves.

The testrig has also been used to validate and update the theoretical models and a good correlation between experimental and simulated data was obtained. The good match between simulations and experiments implies that the developed computer models may be used for predicting the system performance at different running conditions.

Some preliminary simulation results were shown using a realistic environment with a typical slowly varying wave climate combined with irregular momentary waves. A simplified regulation system was then implemented to keep the counterweight position within the limits of a specified displacement range. The very promising results obtained motivate further research and development of the concept. The investigation shows that the concept enables a high capacity factor in combination with the use of existing type of components making cost-efficient wave energy conversion feasible.

The simulation models are currently being improved to include hydrodynamical effects, a more refined regulation system and enhanced models of the actual generator. In parallel, work is carried out to develop smaller models for testing in water labs as well as a larger scale-model for future sea trials.

Acknowledgment

This work is sponsored by Ocean Harvesting Technologies AB.

References

[1] H. Bernhoff, E. Sjöstedt, M. Leijon, Wave energy Resources In Sheltered Sea Areas: A Case Study of The Baltic Sea. In *Proc. 5th European Wave Energy Conference*, Ireland, 2003.

[2] Ahlin K, M. Magnevall, A. Josefsson, Simulation of Forced Response in Linear and Nonlinear Mechanical Systems Using Digital Filters, ISMA, Leuven, 444, 2006

[3] Wave Data from SMHI, Swedish Meteorological and Hydrological Institute, Kristianopel, N: 56°10' E: 16°07', 1991

[4] Tucker M.J., Pitt E.G., Waves In Ocean Engineering, Elsevier Science Ltd, United Kingdom, 2001