Development of a multi-bladed 250 kW pitching wave-energy converter

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Abstract

This paper outlines the methodology to develop a multi-bladed 250kW pitching wave-energy converter based on the swaying motion of sea plants in the presence of ocean waves.

The studies presented here focused on model-tank tests together with dynamics (time-dependent) simulations. These tank tests focused on adjusting and optimizing control variables and the geometric design of the device to allow for the achievement of a required power. The main variables considered here were the blade spacing, ballasting, and power capture. Time dependent simulations based on a theoretical model of the system, once validated with the tank tests at different sea-states, ballasts and blade spacings, provided the power output at different wave conditions.

Keywords: Ballasting, spacing, multi-bladed, pitching wave-energy converter, wave power.

Nomenclature

$\dot{\theta}$	= rotational speed of the device
a	= Radius
c_M	= Inertia coefficient for the excitation moment in the Morrison equation.
D	= Diameter
H	= Wave height
h	= Water depth
KC	= Keulegan Carpenter number
L	= Wave length
M1	= No ballasting condition for the tank tests
M2	= Low ballasting condition for the tank tests
M3	= Medium ballasting condition for the tank tests
M4	= Maximum ballasting condition for the tank tests
S	= Blade spacing measured from the centre of the blade
T	= Period

1 Introduction

Dependence on fossil fuels and awareness of environmental issues, like climate change, have been major incentives for the development of renewable energy conversion devices in the last decade. Some technologies like wind and solar have been widely developed. Ocean energy technologies, on the other hand, are still in R&D and demonstration phases. Relatively few prototypes have been installed to date, as the need to fully address problems like survivability, reliability and cost per kWh is critical in order to perform a successful deployment.

The main subject of this paper is the bioWAVE^{TM} device, a multi-bladed pitching wave energy converter. Through the application of *biomimicry*, the device makes use of biologically inspired mechanisms for survival and energy conversion in the marine environment. The design is based on the swaying motion of sea plants in the presence of ocean waves.

Many types of wave converters have been explored in the last few decades. They can be classified according to their oscillation mode. Existing technologies typically use heave, surge, or pitch modes, or a combination of them. Fig. 1 illustrates the difference between these three motions. The bioWAVE^{TM}, uses the pitch mode to harness the power from the waves, utilising relatively small circular cross sectional blades (with respect to the wave length) and multiple blades to increase the device's power capture ability. It also features a novel 'sinking' functionality that allows the device to avoid heavy loading during storm conditions.

This paper describes some of the research and development activities that lead to the current design of the bioWAVE^{TM}. While some of the overall characteristics of the design can be determined using information from the literature, there are specific aspects that must be determined experimentally or through simulations. This study focuses on three specific design aspects: blade spacing, ballasting, and power capture. Tank tests were used to determine the influence of different ballasts and blade spacing in various wave conditions. Time dependent simulations were performed to determine the power output at different sea states and different ballasts.

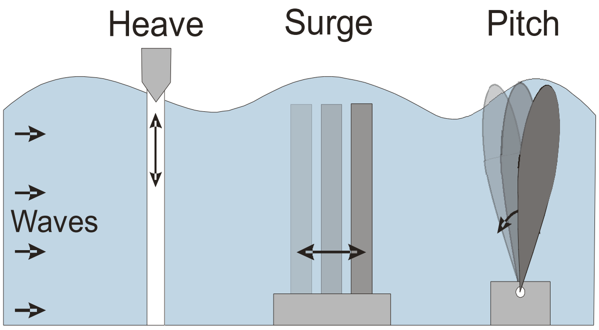

Figure 1: Comparison between heaving, surging and pitching motion.

2 Technology description

The overall shape of the bioWAVE can be seen in Fig. 2. It is a submerged multi-blade structure with the majority of its volume near the water surface. Several works have been followed for achieving this overall shape.

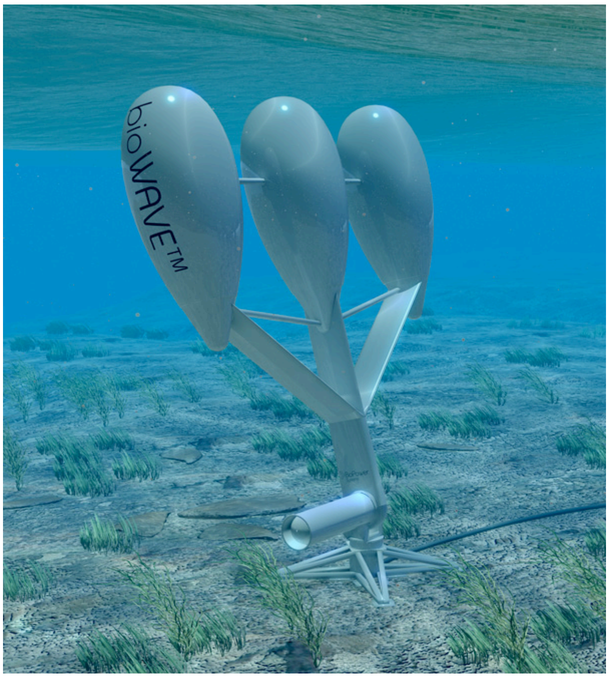

Figure 2: Overall shape of the device.

Budal and Falnes [1] suggested that an efficient wave maker is an efficient wave absorber. A vertical cylinder is a poor wave maker if it has a small a/h, if the incident waves are in the shallow water regime or if the diameter is in the order of magnitude of the wave length (D/L>0.2) [2].

Following the Morrison equation [2], the main power source of a pitching wave-energy converter comes from the excitation moment, which is in turn dependent on local particle acceleration. As maximum wave accelerations and velocities are located near the surface, the device should have more volume and area close to the surface in order to maximize the input power and reduce the amount of material used for the construction of the device.

This hypothesis was evaluated by Flocard et al. [3]. They tested two different cylindrical pitching wave-energy converters, one full cylinder extending from the pivot point to the surface and a shorter one with the same diameter, extending to the surface, but offset from the pivot by means of a relatively thin cylinder. Their tests, conducted in irregular waves, showed that the shorter cylinder presented a higher volumetric capture factor.

Nevertheless, their results showed that the width-based capture factor was larger for the longer cylinder. This, together with the ability to sink in case of storm conditions and a reduced visual impact of the device, allowed us to conclude that the pitching axis should be located at the bottom of the ocean.

As shown by Caska and Finnigan [4], efficient pitching wave converters should be placed in intermediate depths, avoiding shallow water (where wave power decreases substantially) and avoiding deep water where the installation becomes problematic.

Using multiple blades is expected to improve the performance by taking advantage of an increased inertia coefficient to drag coefficient ratio. In this study, three blades were selected following a set of tank tests and the results of Chakrabarti [5] who illustrates the effects of the inertia and drag coefficients for a three-cylinder array configuration and a five-cylinder array configuration. The middle cylinder in the three-cylinder configuration exhibited a higher inertia coefficient than any of the cylinders in the five-cylinder configuration.

Using this information, the shape of the device was designed to have the pitching axis at the bottom of the ocean, with greater area and volume closer to the surface, KC <10 in order to avoid high parasitic drag and multiple blades; each one of them of around D/L≈0.05.

In this design, several design characteristics such as the cross sectional area of the blades, the number of blades, the blade spacing and ballasting have to be resolved. This paper focuses on the latter two, together with the potential for this design to achieve the expected rated power. A circular cross sectional area and a three-blade configuration were selected for this application.

3 Experimental tests

A set of tests was conducted in a 100m long, 3.5m wide and 1.5m deep wave flume on a 1:16 scale model. The tank was instrumented with 3 wave probes at the front, back and side of the device.

The experimental set up was designed to provide a clear assessment of the influence of optimal ballasting, blade spacing and damping of the device on its power capture ability. A waterproof rotational damper was used to simulate a power take off. The model was instrumented with a torque sensor to record the rotational damping moment and a rotational encoder to measure the instantaneous angular position and the velocity of the device, enabling instantaneous calculation of the power extracted from the incoming waves. Three blades with circular cross section were mounted on a rail allowing for adjustment of their spacing. Finally, the ballasting of the device was modified by inserting steel bars of different weight into the core of the blades as displayed in Fig. 3.

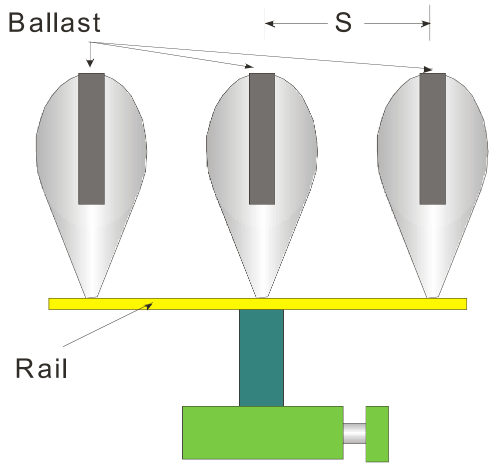

Figure 3: Experimental configuration.

Fig. 4 displays the configuration of the device in a wave tank.

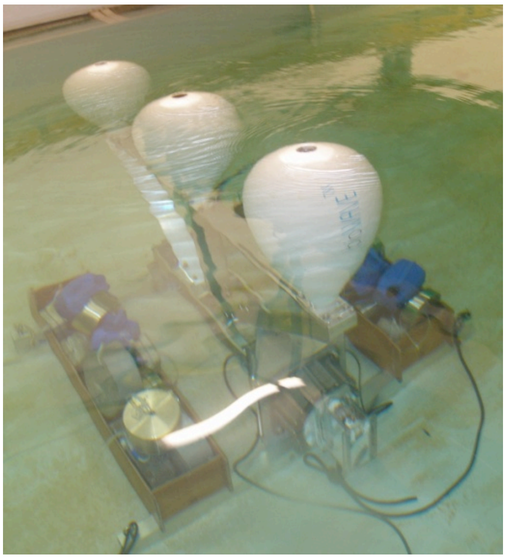

Figure 4: Tank model in the water.

The tests were performed at four different ballasts with maximum spacing and four different blade spacings with minimum ballasting. An optimum damping condition was determined for each test. The test matrix is illustrated in Table 1. In this case, the ballasting was increased from M1 to M4.

The results from these tests were obtained in terms of the power given by equation:

$$Power = Damping \cdot \dot{\theta}^2 \quad (1)$$

Wave height (equiv. full scale) [m]	Period (equiv. full scale) [s]	Ballast	S/D
0.06 (1) 0.09(1.5) 0.12(2) 0.15(2.5) 0.18(3)	2.45 (10)	M2	1 1.333 1.666
0.06 (1) 0.09(1.5) 0.12(2) 0.15(2.5)	2.93 (12)	M2	1 1.333 1.666
0.06 (1) 0.09(1.5) 0.12(2) 0.15(2.5) 0.18(3)	2.45 (10) 2.93 (12)	M1 M2 M3 M4	2

Table 1: Tank test matrix.

The results of these studies indicated that the optimal blade spacing depends on wave conditions as illustrated in the power curves of Fig. 5.

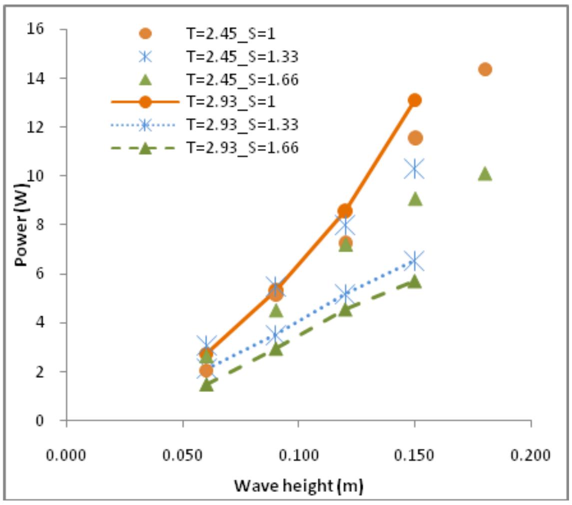

Figure 5: Influence of blade spacing on the power at different wave conditions.

At greater wave heights, S/D=1 performs best while at smaller wave heights and shorter periods, S/D=1.33 gives the best results in terms of power capture.

This agrees with the results of Chakrabarti [5] who worked with multiple cylinder array configurations in an oscillating flow. In his results, at S/D>2 the drag and inertia coefficients (c_M) did not differ from those for a single cylinder at the corresponding KC and Re values. For a three-cylinder array configuration at KC<10, his results show that the inertia coefficient increased by 8 times for the central cylinder when comparing a S/D=1.1 with a S/D=2. The drag coefficient only increases by 4 times for the same cylinder. The outer cylinders behaved similarly; the inertia coefficient increased by 4 times while the drag coefficient increased by 3 times.

As illustrated in Fig. 6, our results showed that optimal ballasting depends on the wave conditions. At small, higher frequency waves, the power was not sensitive to the change in ballast. At larger and especially longer period waves, increased ballasting performed better.

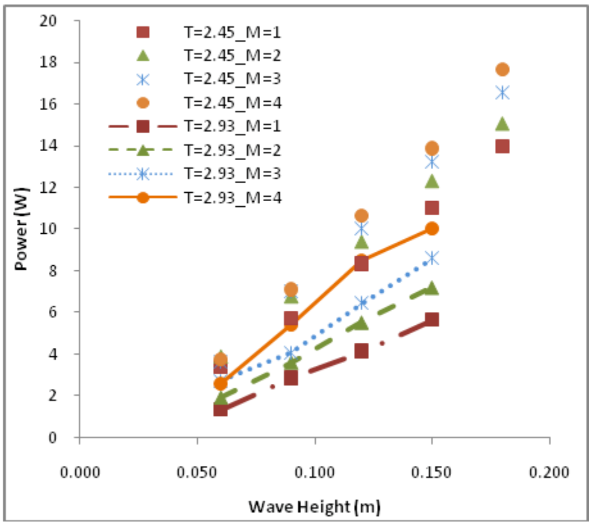

Figure 6: Influence of ballasting on the power at different wave conditions. M1 no ballasting, M4 maximum ballasting.

This effect was also analysed by Flocard et al [3] who considered the use of different ballasting. Their results show that the ballasting for optimal power capture varies depending on the season or the size of the waves - a less ballasted cylinder presented increased power capture for smaller waves, while for larger waves, the more ballasted cylinder performed better.

These results indicate that there can be a further improvement by having a device with variable ballasting.

Using the Froude scaling for these results of Fig. 6, it can be observed that the S/D=2, M=4 configuration would theoretically be capable of achieving 333 kW at a H=3m, t=10s regular wave. Assuming a 15% loss, due to an irregular wave field [6], and 20% losses in generation and transmission, this configuration would be capable of producing 226 kW under such conditions. With higher wave conditions and using optimised blade spacing, this machine could produce the rated power of 250 kW.

4 Time dependent simulations

a. Model development and validation

A Matlab/Simulink model of the bioWAVE™ was developed, based on the set of equations described by Caska and Finnigan [4]. Drag coefficients were obtained from Faltinsen [7] while radiation coefficients were obtained from selected tank test cases at maximum blade spacing. This model was later validated with different tests at several wave conditions and ballasting and maximum blade spacing.

Fig. 7 and Fig. 8 illustrate the differences between the predicted and the measured damping torque and angular position at the equivalent wave height of 2.5m and period of 12s. The plot in blue indicates the simulated data while the one in red the experimental one.

While some differences can still be observed, especially at the maximum and minimum torque, the overall agreement in terms of shape and period is considered acceptable. The difference between the experimental and simulated power is illustrated in Fig. 9. For the T=2.93s H=0.15m, M1 test, the maximum power is within 0.47% and the predicted power is within 3% at the same condition.

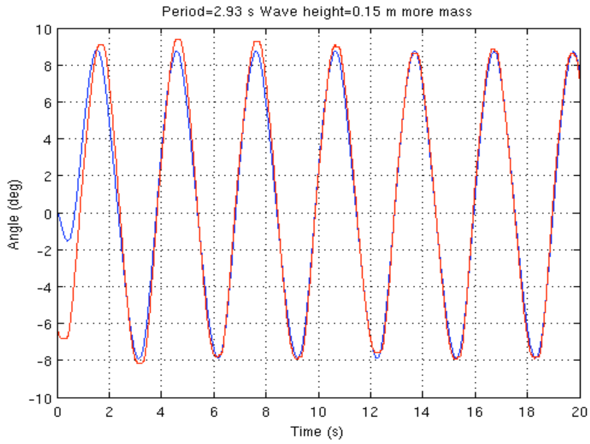

Figure 7: Experimental and simulated angle vs. time at T=2.93s H=0.15m, M2.

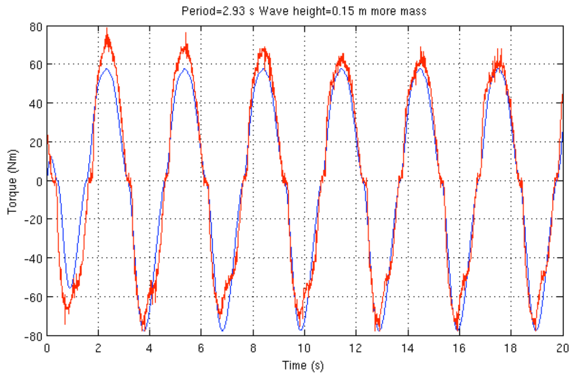

Figure 8: Experimental and simulated damping torque vs. time at T=2.93s H=0.15m, M2

b. Power output

This model was used to predict shaft power of the prototype-scale device at different wave conditions. The dimensions of the prototype-scale are 23.5m long from pivot to tip and 5m maximum blade diameter,

The simulations were run using regular waves, running a four-variable parametric study of T={5.5,6,..,13.5}s and H={0.5,1,..5.5}m. 10 different ballasting values were simulated while the damping was modified between zero damping and the maximum design torque condition. The power was clipped at high frequencies and H>3, since high wave heights are unlikely to happen at such wave periods. Even if such conditions were met, shaft torque would be too high for the power take-off to safely convert power.

Power values obtained from this study are shown in Fig. 10. As observed, the expected shaft power of around 370 kW occurs at wave heights of 4-5m and T=9-10s. Including expected losses from irregular waves and conversion and transport, this gives the rated power of 250kW.

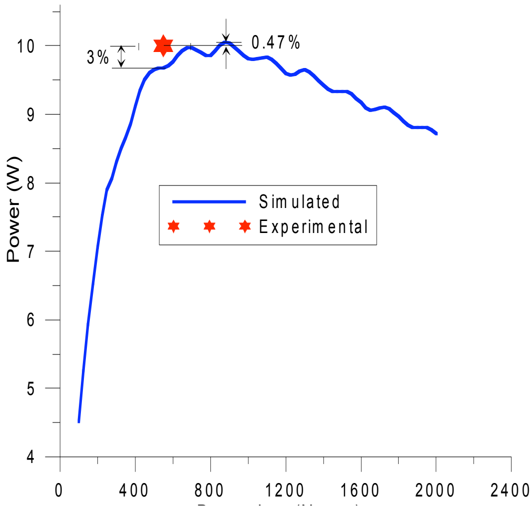

Figure 9: Simulated and experimental power at optimum damping for the T=2.93s H=0.15m, M1 test. The horizontal axis represents the damping as illustrated in equation 1.

These predictions are made for a S/D=2. Output power could be further improved by using more optimal blade spacing.

5 Conclusions

Research and development has been conducted in order to determine effective blade spacing and ballasting of a multi-bladed pitching wave-energy converter and its capacity to produce rated power of 250 kW. This research included tank tests and time-dependent simulations.

Tank tests demonstrate that multiple blade configurations with small spacing (1<S/D<1.3) are more efficient than multiple blades with large spacing. In addition to this, tank tests also indicate that blade ballasting must be adjustable in order to achieve maximum power capture at different wave conditions.

Time dependent simulations, with the support of the results from published experimental data and tank tests, indicate that the achievable shaft-power of this device is of the order of 370 kW at S/D=2. Considering losses, this value equates to the expected rated power of 250kW. Further improvement can be achieved by optimising blade spacing.

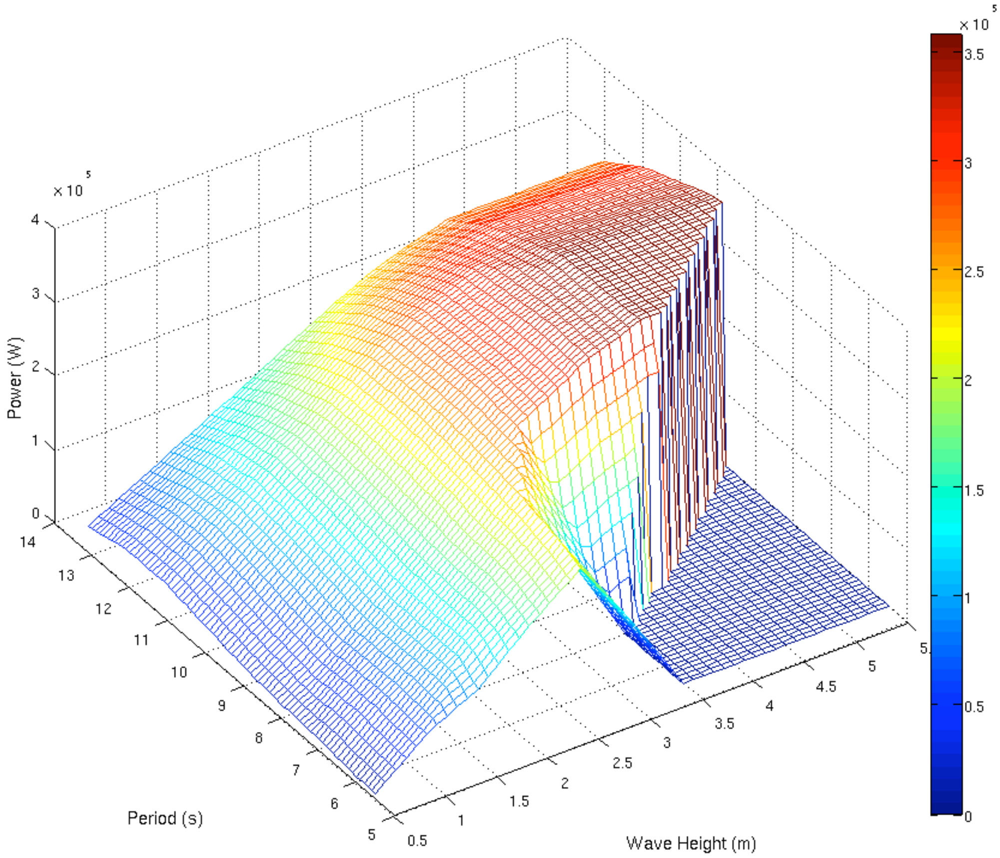

Figure 10: Predicted shaft-power at different wave periods and wave heights

References

1. K. Boudal and J. Falnes. A resonant point absorber of ocean-wave power. Nature. 256, 478-479. 1975.
2. B.M. Sumer and J. Fredsoe. Hydrodynamics around cylindrical structures. Revised edition. Advanced series in ocean engineering, Vol 26. World Scientific, Singapore, 2006.
3. F. Flocard, J.B Frandsen and T.D. Finnigan. Experimental investigation of power capture from pitching vertical cylinders in irregular waves. 2nd international conference on ocean energy. Brest, France. 15th-17th October, 2008.
4. A.J. Caska and T.D. Finnigan. Hydrodynamic characteristics of a cylindrical bottom-pivoted wave energy absorber.
5. S.K. Chakrabarti. Hydrodynamics of offshore structures. WIT press. 1987.
6. J. A. C. Meadowcroft, T. J. Stallard and N. J. Baker. Comparison of power capture in irregular waves and their regular wave components, European Wave and Tidal Energy Conference, 2005.
7. O.M. Faltinsen. Sea loads on ships and offshore structures. Cambridge university press. 1990.