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ANALYSIS OF THE POTENTIAL OF A WAVE ENERGY CONVERSION SYSTEM FOR MALTESE WATERS

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ABSTRACT: This paper presents the analysis of waves in the Maltese waters. Through data analysis the results will highlight the most common waves together with others which yield the largest power. The paper also presents a novel type of wave energy converter with a hydraulic power take off system which is being proposed to be replaced by a linear electric machine. Thus wave data was also analysed with respect to this prototype design. However due to its operational characteristics the design is not an optimal one for the local waters and a point absorber type of converter is suggested. This mechanical structure, in conjunction with the linear machine, shall absorb more power from waves with a large wavelength and a relatively small wave height.

Keywords: Wave energy, electrical generator, energy conversion

1 INTRODUCTION

1.1 Wave Energy

Energy generation from renewable sources, such as wind, waves and solar, is a continuously developing sector which is slowly replacing the use of some of the traditional ways of energy generation. In view of the fact that wave energy convertors extract energy from the sea surface and hence do not extend to high elevations above sea level, their visual impact is of a much lesser concern than offshore wind turbines. Consequently they may be located closer to the shoreline. Wave energy offers the potential of becoming an ideal alternative to conventional energy technologies for countries like Malta which possess large territorial waters and limited land area.

1.2 Wave Energy Converters

Wave energy converters (WEC) differ from each other depending on the way they interact with the waves, on the position of device in relation to the shoreline, distance to seabed and typical wave behaviour.

Prior to determining the most suitable WEC, a study of the waves' heights and periods needs to be carried out. Such parameters will also determine whether the device will be fixed to the shoreline, moored close to the shoreline or offshore. WECs work on a variety of mechanical principles combined with their appropriate power take-off (PTO) method [1].

2 BLUE OCEAN ENERGY PROJECT

The Blue Ocean Energy Project, a project funded by an MCST R&I fund, was launched in Malta by Dexawave Energy Malta Ltd in collaboration with the University of Malta for the purpose of analysing the Maltese wave energy potential. The project also included the deployment of a scaled WEC prototype in Maltese waters, Figure 1.

Figure 1: Artists impression of the proposed WEC [2]

Given that the WEC was originally designed for North Sea conditions, modifications to the prototype need to be carried out in order to optimise it for Central Mediterranean conditions. The operating principle of the WEC may be explained through Figure 2. A surging wave activated body (WAB) type of converter consists of two pontoons linked to a central structure through two independent hinges [3]. A hydraulic double acting positive displacement pump is connected to both pontoons. The waves cause the pontoons to experience angular motion differences in the relative angular displacements of the two pontoons cause the pontoon to pump pressurised oil which is then used to drive the electrical generator. Thus the converter is able to extract the maximum power possible at the bottom of a trough or at the peak of a crest. These positions will result in the largest difference in elevation between the front and rear ends.

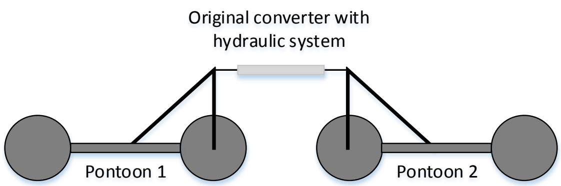

Figure 2: Dexawave WEC design

The study focused on the design of a new electric machine that shall be implemented in the novel WEC. The system shall replace the current hydraulic pump, thereby enabling the WEC to generate electricity directly and eventually be connected to the grid. A local study was also carried out to assess the suitability of such a WEC for the waves present in the Maltese waters. The wave observations consisted of Significant Wave Height H_s and Zero Up-crossing Period T_z where H_s is the mean of the highest one third of the waves while T_z is the average time between two successive point crossing the mean sea level (MSL). These values are collected every 30 minutes by a dedicated Datawell buoy moored off the North West side of Gozo at a depth of 200m.

The wave buoy was deployed within the ambit of the Blue Ocean Energy Project and the data series elaborated by the Physical Oceanography Unit of the University of Malta spanned from 1/10/2011 to 31/9/2012. The collected wave data was analyzed through numerical analysis and graphical representations. Apart from assessing the wave energy potential in the Maltese waters, the wave measurements formed the basis for designing the new generator optimised for the local marine conditions.

3 POWER IN WAVES

3.1 Wave formation

Waves, especially in open waters, are mainly influenced by the wind speed and its fetch. The sea depth and bathymetry also affect the wave's characteristics. Figure 3 summarises the parameters required for describing the surface profile of a one dimensional wave.

A wave is characterised by its wavelength L and its amplitude a, which is half the wave height H. The distance from the average height of the ocean's surface (or MSL), to the seabed is d, while the full wave profile is represented by the instantaneous surface elevation $\eta(t)$. The analysis in this study concerns a floating structure, thus velocity distribution within a wave goes beyond the scope of this study and is therefore not taken into consideration here.

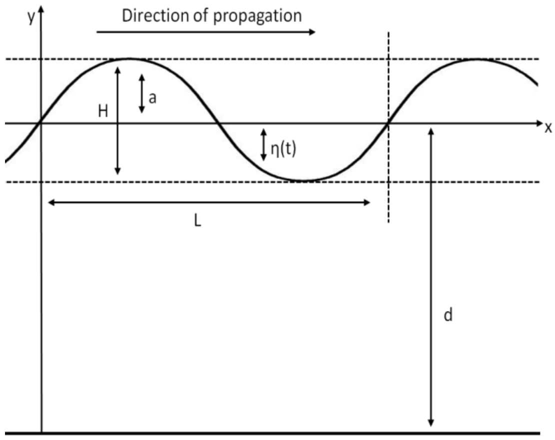

Figure 3: Definitions for a one-dimensional wave

Waves may be classified as shallow, intermediate and deep, depending on the ratio between the wavelength and sea depth (*d/L*).These criteria are summarized in Table I [4].

Table 1: Wave classifications

Wave Classification	Relative Depth
Shallow	$d < 0.05L$
Intermediate	$0.05L < d < 0.5L$
Deep	$d > 0.5L$

3.2 Wavelength and wave celerity calculations

Waves at a sea depths of 200m relative to the observed significant wavelengths are classified as deep water waves and the wave height and period are the only two parameters required to describe the deep wave profile. The Linear Wave Theory [5] in wave analysis describes the wave profile as a function of time t and the horizontal displacement x as follows:

$$\eta(x,t) = \frac{H}{2} cos\left(2\pi\left(\frac{x}{L} - \frac{t}{T}\right)\right) \quad (1)$$

The wavelength L in (1) is also directly proportional to the period T by:

$$L = cT \quad (2)$$

where c is the wave's celerity in the direction of propagation and is equal to:

$$c = \sqrt{\frac{Lg}{2\pi} tanh\left(\frac{2\pi d}{L}\right)} \quad (3)$$

The above equation, (3), needs to be solved iteratively however for deep water waves the hyperbolic expression approaches unity and the wave celerity can be simplified to:

$$c = \sqrt{\frac{Lg}{2\pi}} \quad (4)$$

From the dispersion relation, (3), and (2), L is also directly proportional to the square of the period for deep water waves.

$$L = \frac{gT^2}{2\pi} \quad (5)$$

Substituting (5) in (4) the following relation is obtained

$$c = \frac{Tg}{2\pi} \quad (6)$$

It can be observed that waves with longer periods travel faster than those with shorter ones.

The power in a wave is directly proportional to the period and the square of the wave height. Thus larger powers are generated with waves of large wave heights. The power of a regular deep water wave is expressed as [6]

$$P_{in\ waves} = \frac{\rho g^2 H_s^2 T_e}{64\pi} \quad (7)$$

where ρ is the sea water density, g is the acceleration due to gravity, H_s is the significant wave height and T_e is the energy period. In reality waves are not one dimensional but include a spectrum of harmonics. Thus to cater for multi dimensional waves, including swells and storms the energy period is set to be approximately equal 1.12 of the zero-up crossing period when dealing with actual wave periods [6] [7].

$$P_{in\ waves} = \frac{1.12 * \rho g^2 H_s^2 T_z}{64\pi} \quad (8)$$

The power in waves is expressed in kW per meter of wave front. Thus this value must be multiplied by the converter's width to convert results from power per meter to actual power. Not all the power in a wave is captured by the converter. Consequently an efficiency factor must also be included to compensate for this loss in power. This factor is highly dependent on the design of the mechanical system and its interaction with the waves.

4 DATA ANALYSIS

The wave data through the study described in Section 2 was organised into 3D tables according to different wave heights and periods. Using data records over a year, this analysis gives the number of occurrences of waves with a specific wave height and wave period and thus provides a clear identification of the most common wave profiles.

The analysis of the one year measurements shows that as expected, an increase in wave height brings with it an increase in wave period and the buoy even experienced an extreme 7.5m waves at a period of 8.9s.

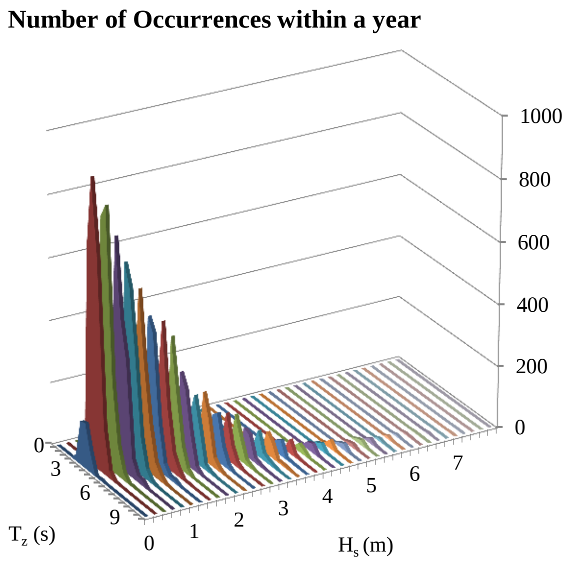

Figure 4: Number of wave occurrences in a year for different significant wave height (m) and zero up-crossing period (s)

The most common waves at the wave buoy station had a time period between 3s and 3.5s and a wave height that varies between 0.2m and 0.4m as in Figure 4. The number of occurrences decreased almost exponentially as the waves increased in both height and period.

However selecting a WEC system is not only dependent on the most common waves as less frequent waves may result in a larger power generated over a period of time. To examine which waves are in possession of the highest energy potential throughout the year, wave data was subsequently analysed in terms the probability of occurrence across the recorded period.

As one might expect through the relation expressed in (8), power in waves is higher for waves with larger wave heights and periods. However the significance of these wave power values must be considered in relation to the amount of time these wave profiles are actually present. The values in Figure 5 are the result of the incident power in each wave, (8), multiplied with the probability of every particular wave as in (9):

$$P_{avg} = \sum_{T_z=0}^{T_{z\,max}} \sum_{H_s=0}^{H_{s\,max}} P_{occ\,(T_z,H_s)} P_{in\,waves\,(T_z,H_s)} \qquad (9)$$

where

$$P_{occ\,(T_z,H_s)} = \frac{No.of\ occurrences_{(T_z,H_s)}}{Total\ no.of\ samples} \qquad (10)$$

This mathematical analysis resulted in an average annual wave power of approximately 7.8kW/m.

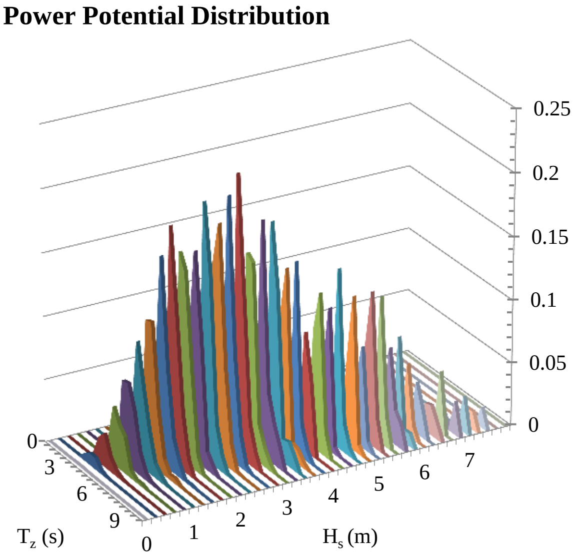

Figure 5: Power potential in waves in a year for different significant wave height (m) and zero up-crossing period (s)

Figure 4 and Figure 5, clearly show that the most common waves did not result in the highest power distributed throughout the recorded year. These calculations show that the waves which yielded most potential over the recorded year were found to have a period between 5.5s and 6s, and a wave height varying between 2.8m and 3m, as shown in Figure 5. Through equation (8), these particular wave profiles are able to create waves whose instantaneous powers can reach up to 26kW per meter.

5 ANALYSIS OF WEC IN LOCAL WAVE SCENARIO

The wave data was then analysed in terms of the operational characteristics of the WEC mechanical structure described in section 2 and Figure 2 to determine the suitability of the proposed WEC system for local waves. Due to its structure, the amount of power absorbed by a WAB converter is highly dependent on the wave's wavelength apart from the wave heights and periods.

A converter whose pontoons are equal to half the wave's wavelength would be the most efficient as these instances would provide the maximum displacement at the PTO component. This may be easily noted in Figure 6.

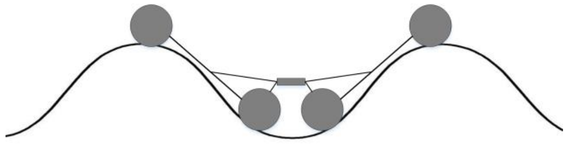

Figure 6: Most efficient WEC length

At instances where the wavelength exceeds the converter's length, the converter's pontoons are still displaced but extract maximum power only at crests or troughs. However, in the case of Figure 7, when the wavelength is more than twice the converter's length, the structure will just ride the waves and the relative angular displacement between both pontoons will be minimal. This reduces the wave energy conversion efficiency of the WEC.

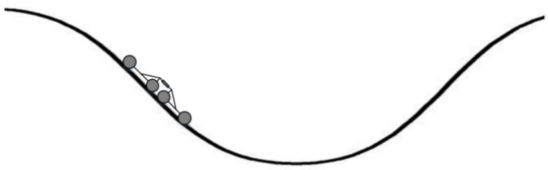

Figure 7: WEC riding the waves

A scaled down model was constructed for experimental purposes. The 1:10 converter model is approximately 7m in length and 2.5m wide. Thus maximum power is extracted with waves at a wavelength of 7m. From (5), these waves have a period of 2.12s and from the records over a year waves with a period from 2s to 2.5s were minimal and exist only at wave heights between 0m and 0.8m. These values yield an insignificant amount of wave energy in Maltese waters as clearly indicated by Figure 5. Moreover, as in Figure 4, these instances are unlikely to occur at the chosen site location and would be uneconomical to design a generator for these low power values.

The design of a structure that shall be able to vary its length to cater for every wavelength and constantly convert the maximum wave power available would result in a rather complex design. However the efficiency of a fixed length WEC may be improved by looking at the most common wave profiles that will generate the maximum power throughout the whole year. This would result in designing a fixed WEC with the most effective length.

From this analysis it was apparent that a larger mechanical structure would work more efficiently at the most common wave periods and heights. The converter can either be designed for values of wave height and period with the highest occurrence or for those that would eventually generate most power throughout a longer period. As explained in section 4, the maximum energy available for conversion is for waves with a period ranging from 5.5s to 6s and wave heights ranging between 2.8m and 3m. But to be able to extract the largest power from the waves the converter's length must match with the wavelengths of such waves. From (5), for a period of 6s, the ideal WAB would be 56.2m in length.

It was also noticed that a WAB type of converter is also dependent on the ratio between the wave height and its wavelength. A 56m wave has a maximum wave height of just 6m. This implies that even though the structure is large enough to extract maximum power at a wave's crest or trough, the height is insignificant when compared to the converter's dimensions and the ratio between the wave height and half its wavelength result in a very small elevation angle. (To represent this scenario pictorially, similar to that in Figure 7, would result in a wave which would look like a straight line over the length of the wave. In this respect such a figure was omitted from the paper).

Consequentially the structure will not have enough displacement at the PTO module to generate large amounts of power. In hydraulic PTO systems this drawback could be compensated with larger pistons or by operating with more pressurized fluids to capture larger forces with small displacements. However in this project it is being proposed to replace the current PTO system with a linear machine for which these adjustments do not apply.

For these reasons this WAB system is not the most suitable for the type of waves which prevail in local waters.

6 ALTERNATIVE STRUCTURE

A point absorber type of converter is a more efficient system for local waters since this can utilise directly the full wave height.

Point absorbers are floating semi-submerged devices, as illustrated in Figure 8 [8]. These converters are anchored to the seabed and operate by varying the displacement of the floating buoy from the MSL[9]. Such WEC devices are usually equipped with spring systems at their base to force the buoy downwards with a trough. Point absorbers thus have the advantage of utilising directly all the wave height and due to the buoy's shape and the converter's operational characteristics, they manage to convert wave power independent of the waves' direction [1][6].

Due to the way a point absorber operates it interacts better with the waves' motion than a WAB. Thus a higher capture factor is used for these structures and will therefore result in a larger power absorbed by the mechanical structure for conversion. Furthermore the vertical velocity of point absorbers is only dependent on the wave height and the time the buoy takes to travel from a crest to a trough which are higher than the velocities that existed for the PTO system of the WAB converter.

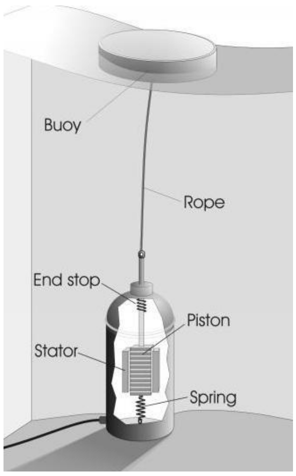

Figure 8: Point absorber converter

These type of converters are usually installed at depths much less than that at the chosen location on the North West side of Gozo. WECs closer to shore have a higher survivability rate and a relatively lower cost related to anchoring, installation and maintenance[1][10]. Even though for deep water waves the seabed is undisturbed by the waves at the surface, long anchoring is required to link the generator to the floating buoy. This will give the buoy the possibility of drifting in the wave's direction of propagation which will therefore reduce the translator's motion and velocity. Installing such systems closer to shore would lead to a higher visual impact from land.

For the research work carried out on the energy conversion with such devices, it shall be assumed that the buoy will follow a vertical motion. This will also imply that the buoy will be large enough to be able to pull the translator's weight upwards and will be continuously floating at the surface, unless the wave height is not beyond the translator's allowable displacement.

7 LINEAR MACHINES

A linear machine operates in a similar way to its rotational equivalent, however it is an unrolled version of the former. A linear electrical system would be suitable for operation with both WAB and point absorbers converters mentioned above. Linear machines can be of the induction, synchronous and switched reluctance type.

Even though induction generators are lower in cost and easy to produce, for the calculated powers at the slow speeds required by the WEC, the design would result in a relatively large size. Thus due to inefficient power to weight ratios, synchronous linear generators are preferred to the induction type. The possibility of designing a linear switched reluctance generator was also eliminated. This was mainly due to the ripple in its output which may be significant at low speeds ..

Thus it was decided to design a linear synchronous generator with permanent magnets in order to be able to convert the power absorbed by the mechanical structure at the low speeds present. The linear machine configuration shall consist of a tubular design with a translator onto which the magnets shall be inserted. The magnetic translator will also be longer than the stationary part to get a smoother output from the armature. Since acceleration is not a significant parameter, the stationary part will be slotted to increase the magnetic flux density. This comes at the cost of increasing the magnitude of other losses [11][12][13].

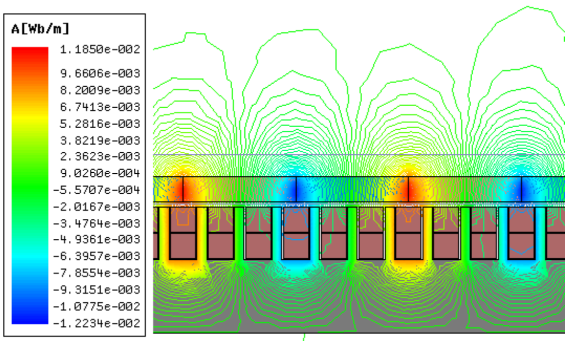

Figure 9: Flux lines of a simulated 8 pole linear PM machine with surface mount magnets in ANSYS Maxwell

The linear machines designed will be initially studied through electromagnetic analysis, as shown in Figure 9 followed by transient analysis. The wave's motion is assumed to be sinusoidal with a varying velocity equal to the wave's profile derivative. The final generator design will also be tested for irregular waves by forcing inputs that may also consider other harmonics with sine waves of different frequencies which are superimposing on a pure sine wave. Analysis is carried out in ANSYS Maxwell and ANSYS Simplorer.

8 CONCLUSIONS

In this paper the performance of a WAB converter was studied to validate its operation in the Maltese waters. Data for the local waves was gathered over a year and it was concluded that the most common waves have a time period of 3.5s to 4s and a wave height varying between 0.6m and 0.8m. However the waves containing the most power potential within a year are those with a period between 5.5s and 6s and a wave height ranging between 2.8m and 3m.

Through the data gathered it was also possible to conclude that a WAB converter is not suitable for the local waves and that a point absorber type might be more productive. The latter was judged to be a better option as the way such a converter interacts with the waves is more effective for waves with a large wavelength and a relatively small wave height. Further to this, the velocity at the PTO module is larger in point absorber converters . This parameter is very important for a linear machine, since the higher the velocity, the higher shall the generated voltage be.

Following the results from the wave analysis a linear machine will be designed to yield the highest potential of power generation throughout the year.

9 ACKNOWLEDGMENTS

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