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Equator-Friendly Ocean Wave Energy Conversion

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***Abstract*—Existing commercialized wave energy converters like the Pelamis device target waves with a mean wave height of approximately 6m. Near-Equator territories (such as the Caribbean, Malaysia, and Egypt) usually boast maximum wave heights of 1.2 m with an average wave height of 0.75 m. Existing wave energy converter designs therefore cannot benefit such territories. Our goal is to optimize wave energy conversion specifically to extract the energy from waves characteristic of Near-Equator latitudes, such as 8-second ocean waves of average height 0.75m endemic to the Caribbean waters.**

***Index Terms*—Wave Energy Converter, Array, Equator, Small waves**

I. Introduction

The concept of ocean wave energy conversion was first written of when early seafarers observed the power of sea waves as they lifted the bows of 20000-ton ships [13, pp.45]. At present over one thousand patented wave energy conversion techniques have been spearheaded to operate under three predominant classifications, namely: Attenuator, Point Absorber and Terminator [8]. Of these patents, successful WEC designs such as the Ocean Power Technologys PowerBuoy and the Pelamis Wave Power device have been implemented to full scale.

Wave energy is created by winds as a by-product of solar energy distribution by the atmosphere. On average, waves have an energy of typically 10 to 100 kW/m [14] [7]. In waters near the equator however, wave power equates in the lowest values, near 15 to 20 kW/m (see Figure 1 in [14]). Although this range falls within the lowest values, 1 km of these waves holds enough power to equate to the total power needs of over 16,300 average US households in a month (the average US household consumes 911 kWh per month).

The Caribbean Small Island States are currently burdened with the highest energy prices in the world which fluctuate greatly with the global price of petroleum [11]. With increasing demands for energy and concern for the environment with regards to harmful emissions of gases released from the burning of fossil fuels to generate electricity, alternative means of harnessing energy must be sought to feed the Caribbean power demands and safeguard the environment. Energy security and alternative energy sources have been of major concern in the Caribbean since the 1970s [1]. Popular alternative energy sources such as solar power, geothermal power, wind power and hydropower have been utilized over the years but the peoples of the Caribbean have negated the sea which could potentially power all their homes. As the Caribbean has a high sea to land ratio, harnessing energy from the sea is an ideal option. Most successful wave energy converter designs on the market are designed for the wave climates in higher latitudes. From the high-latitude territories, much of the global scientific output originates [16]. Figure in [16], which plots global territory sizes re-scaled in proportion to the number of papers published in 2001 that were written by scientists living there, shows a graphical depiction of the global imbalance in scientific knowledge, and partially explains the absence of published research on wave energy conversion for near-equator territories. Unlike most successful designs on the market, the Sea Force Energy (SFE) WEC is being designed specifically for smaller wave heights, less than 2m, which are all considered idle or useless for the Pelamis and comparable designs. Figure 20 in [11] shows that the Pelamis device, like most other successful wave energy converters, operates optimally in waves of heights of 5m to 8m with periods of 6.5 seconds up to 12.0 seconds, considering the waves primarily characteristic of the Caribbean sea (less than 1m wave height) to be ”idle” and therefore useless.

Large arrays of smaller point absorber units are more suited to the small ocean waves near the equator and these are easier to transport and maintain. This evidently minimizes the cost of materials and reduces the fluctuations in power generation as multiple devices in an array can be optimized in a wave-environment to be all activated out of phase from the rest of devices [2]. Arrays are important as their optimization can lead to substantial multiplications in the total electrical energy produced by the WECs. Array optimization depends on the geometry of the system, interspacing between the WECs and orientation relative to the incoming wave’s directional spectrum. Arrays are advantageous as many small units in proper orientation can produce the same energy as a single large unit.

II. Design, Build and test of small-scale models of the Seaforce Energy Wave Energy Converter Array System

The Seaforce Energy Wave Energy Converter Array design is designed to target the smaller waves of the ocean. The model is tested via two scaled-down experiments, namely a one-tenth-scale array to study the dynamics of the WEC bodies in waves at Crews Inn Bay, Trinidad (see Figure 3) and also a $\frac{1}{25}^{th}$-scale model of the hydraulic take-off system proposed for the WEC device using local oceanic wave data from Las Cuevas Bay, Trinidad, (see Figure 3). To remove the complexities of deep-water testing, both test sites contain smaller-than-average ocean waves in very shallow (therefore higher-friction and lower-energy) areas.

Using similitude, the results from these two scaled-down model tests are scaled up to project the full-scale behavior of the system.

III. Testing of 1:10 WEC device arrays’ output movement

Seven one-tenth-scale wooden models of the proposed Seaforce Energy Wave Energy Converter (WEC) devices,

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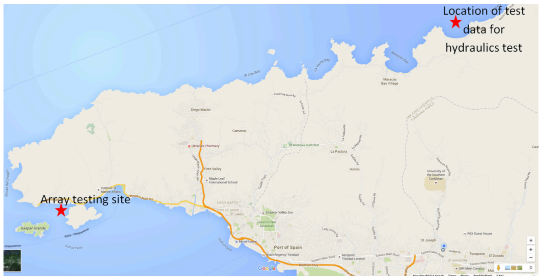

Fig. 1. Test and source-data shallow-water locations for the one-tenth-scale array testing and the one-twenty-fifth-scale hydraulic modeling, (taken from Google Maps).

termed Ocean Responsive Vessels (ORV's) are built and deployed into arrays consisting of increasing values of n (the number of devices in the array) as shown in Figure 2.

Accelerometers are installed on each of the seven devices and they are deployed in arrays from n=3 up to n=7 devices, to test the effect of arraying. This test is executed in a shallow (7m depth) area of Crews Inn Bay, Trinidad (see Figure 3), to allow for short mooring lines and easier control of array shapes.

Despite these measures, due to current and tidal shifts, strong drifts of the devices occur (as described in Figures 4, 5, and 6) and these changes impact on results as described in Section IV.

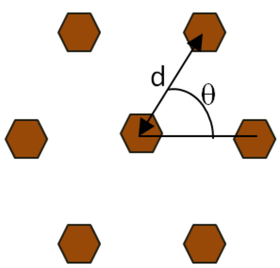

Fig. 2. Wave Energy Converter (WEC) array schematic, whereby d and θ are approximately adjusted as n (the number of devices) is increased from n=1 up to n=7.

Fig. 3. Wave Energy Converter (WEC) array test in Crews Inn Bay, Trinidad.

Deployment Time	9:15-9:35	10:13-10:33
Number of Devices, n	n=1	n=3 d
Comments	Baseline result	Devices drifted towards each other, Unknown d
Number of ship wakes	4	1

Fig. 4. Description of first two tested arrays' deployment times, number of concurrently passing ships, and description of drift.

Deployment Time	10:49-11:09	11:24-11:44
Number of Devices, n	n=4 d	n=5
Comments	Larger d than when n=3. Drift.	
Number of ship wakes	3	2

Fig. 5. Description of second two tested arrays' deployment times, number of concurrently passing ships, and description of drift.

Deployment Time	12:00-12:20	12:44-13:04
Number of Devices, n	n=6	n=7
Comments	Large drift. Fully modified array shape.	Rising tide - Large drift.
Number of ship wakes	0	1

Fig. 6. Description of final two tested arrays' deployment times, number of concurrently passing ships, and description of drift.

IV. Analysis of 1:10 Scale Model of Device Array Output Movement

Movements of the WEC bodies show wave-like characteristics as they respond to the surrounding ocean waves in the field test.

We now compare the mechanical power transmitted to the first deployed WEC before arrays are implemented (baseline readings taken from and after arrays are implemented.

The equivalent wave-like responses detected in WEC motion includes the effects of the incoming waves and the effect of arraying as the value of n is increased beyond n=1. From the accelerometers, acceleration is read, and acceleration is then numerically integrated twice to find WEC displacements. Wave heights were defined using a

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mean-up-crossing method, whereby a crest is defined as the maximum displacement between every two consecutive up-crossings around the mean displacement, and the trough is defined as the minimum displacement between every two consecutive up-crossings around the mean displacement.

In ocean water, (density, $\rho = 1030kgm^{-3}$, under the influence of gravity, $g = 9.81ms^{-2}$, wave height, H) total power, P, input from the waves into the WEC body is calculated as follows:

$$P = \frac{1}{2}\rho g|H|^2 C_g, \tag{1}$$

[14]. The group velocity of the wave group, C_g, is defined as follows:

$$C_g = \frac{\omega}{2k}\left(1 + \frac{2kh}{sinh(2kh)}\right) \tag{2}$$

where the angular frequency of the wave, $\omega = \frac{2\pi}{T} = \frac{2\pi\ rad}{8\ s} =\ 0.785\ rad/s$, and the wavenumber of the wave, $k = \frac{2\pi}{\lambda} = \frac{2\ \pi\ rad}{100\ m} = 0.063m^{-1}$ and the bottom depth, h=7m. Note that we can estimate that wave period, T $\approx$ 8 s, and wavelength, $\lambda \approx$100 m, from previous knowledge of the local wave characteristics [11].

Due to the cyclic vertical displacement of the wave energy converters in the wave environment, "wave heights" are transferred to the WEC bodies in the ocean waves. From these transmitted wave heights, Figure 7 shows the Power transferred to the WEC bodies, and this is scaled up to full scale based on Froude Similitude, shown in Figure 8.

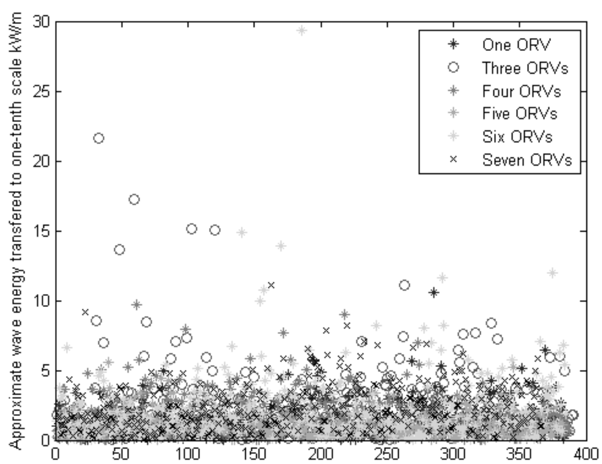

Fig. 7. Comparison between mechanical power transmitted to the first deployed device before and after arrays are deployed. Wave Power calculated from Wave Heights detected by one-tenth scale WEC bodies in arrays of increasing n-values from n=1 to n=7.

Froude similitude between the full scale prototype, p and the one-tenth scale model, m, would require that:

$$\frac{V_p}{\sqrt{l_p g}} = \frac{V_m}{\sqrt{l_m g}}, \tag{3}$$

where we can define the characteristic speed for a heaving device as

$$V_p = \frac{H_p}{T_p}.$$

Similarly, in the one-tenth scale model,

$$V_m = \frac{H_m}{T_m}.$$

Knowing that the length ratio,

$$\frac{L_m}{L_p} = \frac{1}{10},$$

and that $T_p = T_m$, putting all together, we can conclude that

$$\frac{P_p}{P_m} = \frac{\frac{1}{2}\rho g|H_p|V_p}{\frac{1}{2}\rho g|H_m|V_m}. \tag{4}$$

This implies that

$$\frac{P_p}{P_m} = \frac{H_p^2/T_p}{H_m^2/T_m} = \frac{H_p^2}{H_m^2} = 10^2. \tag{5}$$

Thus we conclude that

$$P_p = 100P_m. \tag{6}$$

This implies therefore that scaling up power values to the full scale simply requires a multiplication of the power in the model by 100.

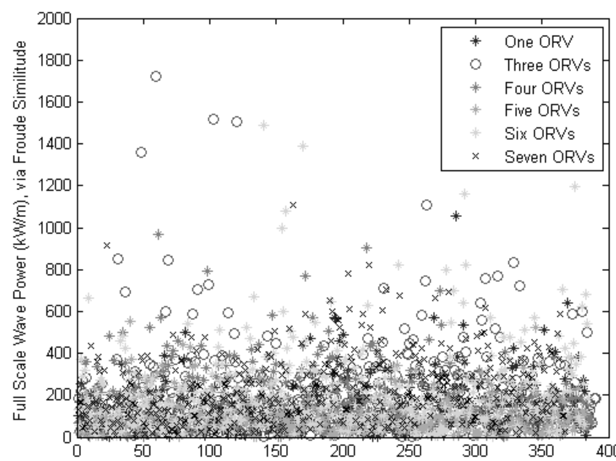

Fig. 8. Comparison between mechanical power transmitted to the first deployed device before and after arrays are deployed. Scaled up Wave Power calculated using Froude Similitude for increasing n-values from n=1 to n=7.

One measure of the effect of arraying is the direct quantitative comparison between the varying results for n-values and the baseline result, and in Figure 9, we see that for this model scale the most efficient value at n=3, with the highest array effect, but that destructive effects of the array were seen when n=6.

V. ANALYSIS OF 1:25 SCALE MODEL OF SYSTEM'S POWER TAKE-OFF.

The present $\frac{1}{25}^{th}$-scale hydraulic system model (see Figure 10) is tested using ocean surface elevation data from Las Cuevas Bay, Trinidad (See Figure 3) to power a linear actuator to move as though being heaved by the ocean surface at that location to manipulate a hydraulic piston and produce a pressurized fluid. Changes in fluid pressure are detected

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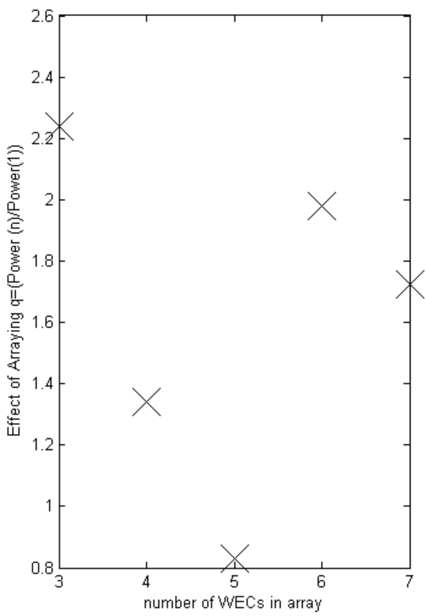

Fig. 9. Comparison between mechanical power transmitted to the first deployed device before and after arrays are deployed. These show the comparative effect of Array on Wave Power efficiency for increasing n-values from n=1 to n=7.

with a pressure gauge and flow rate is detected with a flow meter. These two are used to calculate the power produced by the system as follows:

$$Power(hp) = \frac{[Pressure(psi) \times Flowrate(GPM)]}{1714} \quad (7)$$

This calculation is then scaled up to full scale using Froude Similitude and results of this scaling are shown in Figure 11.

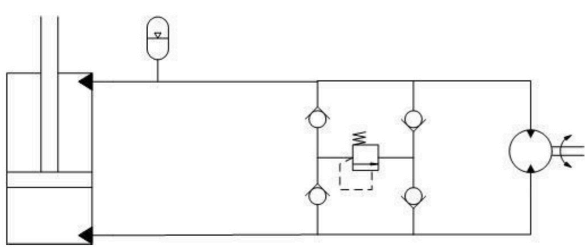

Fig. 10. Hydraulic system design.

Output power values (see Figure 11) show scaled up values near 8 W per device at maximum, and these are scalable by the present results up to just over 17.6 W per device.

VI. Discussion and Conclusions

The output power values scaled up from the hydraulic system in an array are low in the absence of more optimization of arrays, greater optimization of hydraulic Power Take Off, and deeper water.

In spite of this, output hydraulic power is projected. Also, despite experimental challenges, the effect of arraying was distinctly detected. Despite less-than-ideal conditions in the present tests, results are promising and further probing must be done in this region which remains mostly untouched by wave energy conversion techniques.

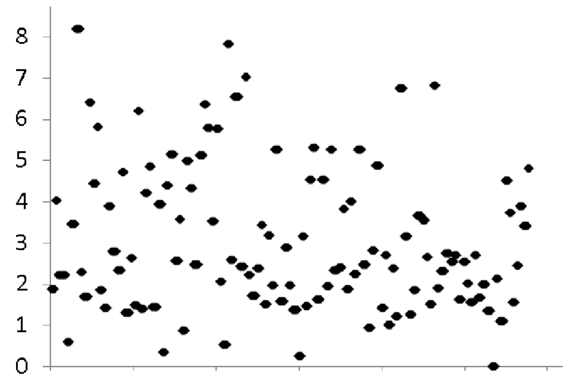

Fig. 11. Scaled-up Power output in watts, W, produced from results of hydraulic power take off system, using Froude similitude.

References

[1] Affonso, S., Dominic, D.(2010) Confronting the Energy Security Dilemma of the Caribbean. *International Public Policy Review*.

[2] Babarit, A., Tissandier, J., and Clment, A. (2008). Study on the smoothing effect of the power production in an array of SEAREV wave energy converters. *18th International Offshore Polar Engineering. Vancouver, BC, Canada.*

[3] Bridge, J. (n.d.). *A First Course In The Mechanics of Machines.*

[4] Cargo, Christopher (2012). Design and Control of Hydraulic Power Take-Offs for Wave Energy Converters. *A thesis submitted to the Department of Mechanical Engineering, University of Bath.*

[5] Casey, Sean (2013). Modeling, Simulation, and Analysis of Two Hydraulic Power Take-off Systems for Wave Energy Conversion. *A thesis submitted to Oregon State University.*

[6] Castillo, J. M. (2000). Symbolic Computation of Planetary Gear Train Efficiency.*European Congress on Computational Methods in Applied Sciences and Engineering.*

[7] Cruz, Joao. (2008). Ocean Wave Energy: Current Status and Future Perspectives . *Berlin Heidelberg: Springer-Verlag.*

[8] Drew, B., Plummer, A. R., Sahinkaya, M. N. (2009). A review of wave energy converter technology. *Proc. IMechE Vol. 223 Part A: J. Power and Energy.*

[9] Green, W. G. (1962) *Theory of Machines.*

[10] Grote, K.-H. A. (2009).*Springer handbook of mechanical engineering Grote, Antonsson (Eds.).*

[11] Henry, L., Bridge, J., Henderson, M., et. al. (2015). Key factors around ocean-based power in the Caribbean region, via Trinidad and Tobago. *Renewable and Sustainable Energy Reviews.*

[12] Lasa, J., Antolin, J. C., Angulo, C., Estensoro, P., Santos, Ricci, P. (2012). Design, Construction and Testing of a Hydraulic Power Take-Off for Wave Energy Converters. *Energy Unit, Tecnalia, Mikeletegi and Mechanical Engineering Department, University of the Basque Country, Alameda.*

[13] McCormick, M.E. (1981). Ocean wave energy conversion, Alternate energy. *Wiley Medical Publication.*

[14] Mei, C. C. (2012). Hydrodynamic principles of wave power extraction. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences.*

[15] Mitchell, J. S. (1981). *Machinery analysis and monitoring.*

[16] Newman, M. (2006). Worldmapper.org. *SASI Group, University of Sheffield, University of Michigan*

[17] Energy Technology Support Unit (ETSU), (2007). Ocean Power Delivery Ltd New and Renewable Energy Programme. *UK Department of Trade and Industry, UK.*

[18] du Plessis, Jacques (2012). A Hydraulic Wave Energy Converter. *Department of Mechanical and Mechatronic Engineering, University of Stellenbosch, Private Bag X1, Matieland 7602, South Africa.*

[19] Reyes, Hctor Fabin (2013). WaveNET Efficiency Improvement (Hexagonal Array Wave Energy Converter System). *AlbaTERN Ltd., Midlothian Innovation Centre Edinburgh.*

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References reformatted