A ROW SPACING STUDY FOR WAVE ENERGY CONVERTER ARRAY OPTIMIZATION

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INTRODUCTION

In order to meet growing energy demands, and to utilize energy sources that are renewable, research and development is being conducted to determine efficient and cost-effective methods of extracting energy from the ocean's waves, tides, and currents [1]. The estimated 16,000 – 18,500 TWh of global energy in the ocean waves makes extraction of this energy for use by the large portion of the population living near a coastline highly promising [2,3].

As the industry moves closer to widespread ocean deployment of wave energy converters (WECs), the next step is to consider the deployment of multiple devices acting together in array scenarios. As has been observed with the research and implementation of wind farms [4], the configuration of individual devices in relation to each other can vastly influence the power produced, economics involved, and environmental and social impacts.

With the many potential factors impacting arrays, it is vital that tools are created that realistically inform developers about the deployment of optimal WEC farms. To best account for the factors involved, it is useful and necessary to utilize optimization techniques; however, at this stage in WEC array design research, most work assumes prescribed layouts based on basic assumptions; little research has been conducted regarding the use of optimization methods for array configuration. As an extension of the optimization work previously conducted by the authors, this paper investigates how generated power is influenced by the separation distance between two rows of parallel wave energy converters perpendicular to a unidirectional wave field.

PREVIOUS ARRAY DESIGN WORK

The wave energy industry has learned from wind farm layout research regarding the consideration of array design [4]; however, unlike wind, where fluid interaction between the devices is generally negative, wave energy converters have the potential to generate more power when placed in an array than the amount of power generated by an equal number of devices acting in isolation [5]. Eq. 1 shows the formulation for calculating this interaction factor, q.

$$q = \frac{P_{array}}{N \cdot P_{isolated}} \tag{1}$$

where P_{array} is the power generated by the array, $P_{isolated}$ is the power generated by a device in isolation, and N is the number of devices in the array. A value of q that is greater than one represents an array which is positively benefiting from device interaction, and a value less than one represents device interference.

A majority of research investigating the configuration of arrays use assumed layouts based on geometric shapes such as squares, triangles, diamonds, stars, single rows, and parallel offset rows [6–10]. Beyond the research involving assumed layouts, there is some work investigating the use of optimization methods for determining layouts. A heuristic algorithm in combination with a convex optimization solver is used by Snyder and Moarefdoost such that symmetry is assumed [11]. McGuinness and Thomas examine the optimal spacing between devices when the WECs are constrained to act in a line parallel to the oncoming wave [12] and the work of Child and Venugopal utilizes a parabolic intersection method and MATLAB'S genetic algorithm (GA) toolbox to determined optimal arrangements of five heave constrained devices in a regular sea [13–15].

Previous work by the authors introduces a customized genetic algorithm method used for determining optimal arrangements of five WECs (similar to those devices used in [15]) in a discrete space. This work is novel in it's implementation of a customized genetic algorithm, and the inclusion of cost in the objective function equation [16,17]. Further investigation of varying numbers of devices reveals the WECs arranging themselves in two parallel lines perpendicular to oncoming wave field with a consistent spacing between rows. Figure 1 shows an example of the spacing seen with 20 devices (unidirectional waves are coming from the the left).

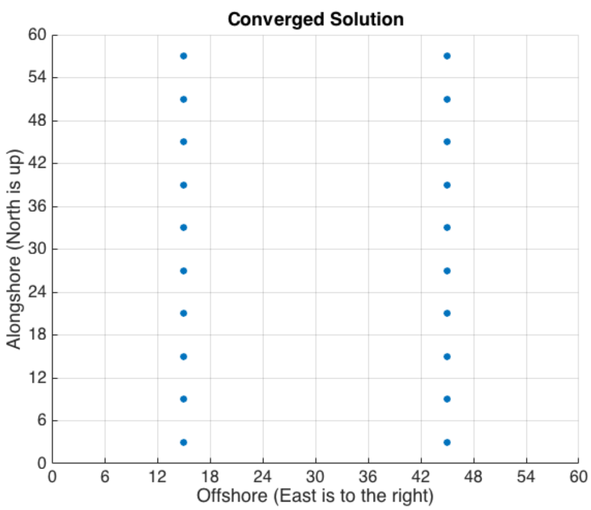

FIGURE 1: OPTIMAL ARRANGEMENT FOUND FOR 20 DEVICES

To better understand this spacing effect, a specific study with 20 devices was performed and is discussed here.

STUDY PARAMETERS

For this study, the scaled device modeled is a truncated cylinder constrained to act in the heave direction. The radius is one meter and the draft (distance of the device below the free water surface) is also one meter. These devices are placed in a water depth of eight meters and the arrays are subjected to a wave field derived from a Bretschneider spectrum that has a modal frequency of 0.2 Hertz and a significant wave height of two meters. These parameters are the same as used in previous research by the authors [16].

In the current study, the interaction factor of configurations at different prescribed spacing are compared. The interaction factor, q, is determined using Eq. 1. The power is calculated by first using the hydrodynamic properties of a single WEC, calculated using WAMIT [18], to determine and array's added mass and damping as well as a single device's diffraction matrix, radiated wave coefficients, and force transfer matrix. With this information, total power is calculated following the method discussed my McNatt et al. [19] and using Eq. 2.

$$P = \frac{1}{8}\mathbb{X}^{*}\boldsymbol{B}^{-1}\mathbb{X} \tag{2}$$

where $\boldsymbol{B}$ is the array's damping and $\mathbb{X}$ is the complex exiting force [20].

The initial starting point of the study fixes the up-wave row of devices at the front of the space with six meters between each device alongshore. The secondary row is initially placed six meters down-wave from the fixed row and subsequently moved to the right in small increments.

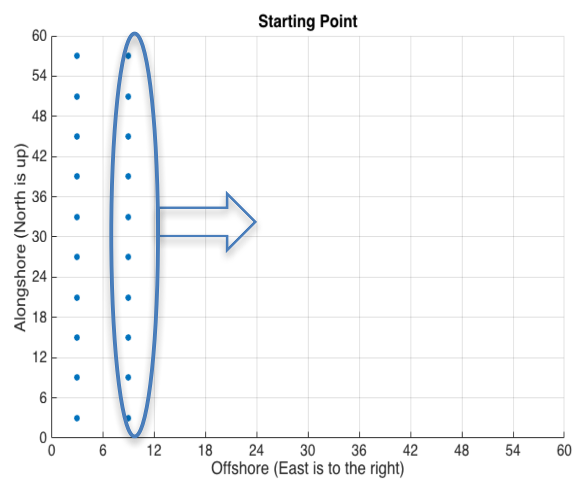

FIGURE 2: STARTING POINT FOR THE ROWS OF DEVICES

Several different scenarios are considered. In the first, the space is constrained to the 60 x 60 meters (shown in Figure 1) and the location with the maximum interaction factor is determined. The second scenario increases the space in the offshore direction to determine if a more optimal spacing exists beyond that which is found in the first scenario. The third consideration evaluates the trend of the interaction factor as the space changes.

ROW SPACING STUDY

For the first scenario the optimal spacing is found in a 60 m x 60 m space. Figure 3 shows the interaction factor as a function of the distance, in meters, between the device rows. The results are evaluated at quarter meter intervals.

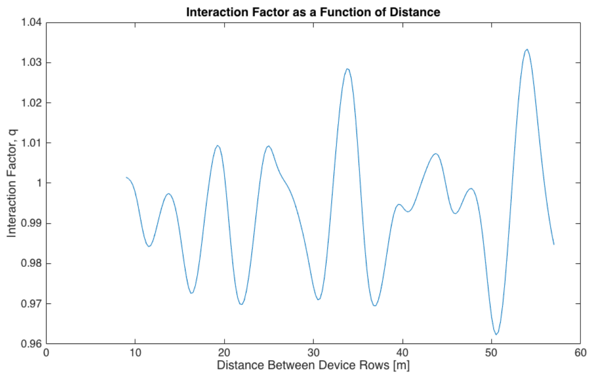

FIGURE 3: INTERACTION FACTOR AS A FUNCTION OF DISTANCE BETWEEN ROWS FOR A 60 X 60 METER SPACE

From these results a maximum interaction factor of 1.0334 is found at a spacing of 51 meters and is shown in Figure 4. The second best interaction factor of 1.0284 is located at a spacing of 30.75 meters.

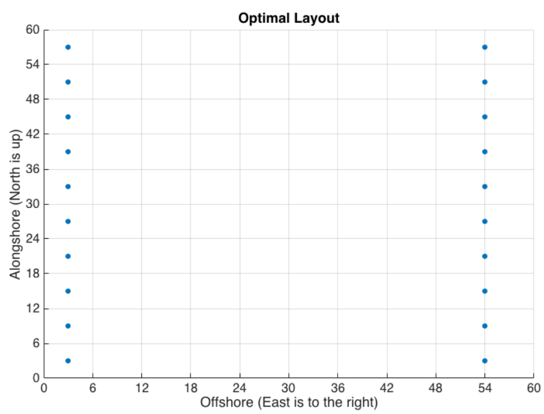

FIGURE 4: OPTIMAL SEPARATION SPACING IN A 60 X 60 METER SPACE

When the distance offshore is increased from 60 meters to 700 meters, the results obtained are shown in Figure 5. For these results the interaction factors are evaluated at one meter intervals.

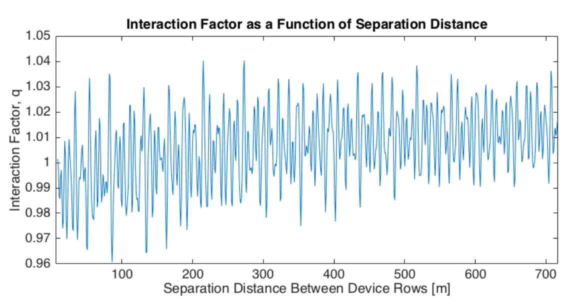

FIGURE 5: INTERACTION FACTOR AS A FUNCTION OF DISTANCE BETWEEN ROWS FOR A 60 X 700 METER SPACE

With the increased distance offshore, the maximum interaction factor of 1.0403 occurs at a separation distance of 270 meters. As an alternative consideration, the row of devices to be moved are offset in the alongshore direction – shown in Figure 6.

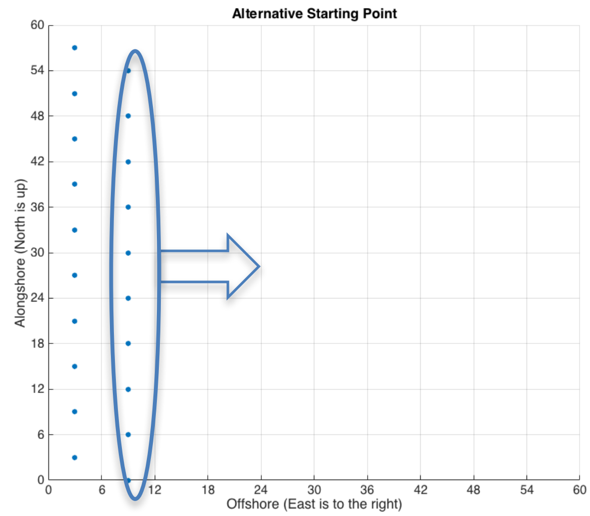

FIGURE 6: ALTERNATIVE STARTING POINT FOR THE ROWS OF DEVICES

Resulting behavior of the interaction factors for the 60 m x 700 m space is shown in Figure 7.

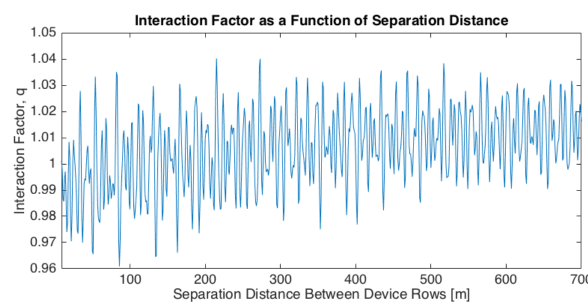

FIGURE 7: INTERACTION FACTOR AS A FUNCTION OF DISTANCE BETWEEN OFFSET ROWS FOR A 60 X 700 METER SPACE

The offset lines yield a maximum interaction factor of 1.401 at a spacing of 212 meters and again at 270 meters. Lastly, the interaction factors every two meters are found for a 60 m x 1400 m space. The maximum interaction factor (and its location) is the same as the 60 m x 700 m case, but these results are generated to observe the overall behavior of the interaction factor as the separation distance increases. The smoothed data approaches an interaction factor of approximately 1.015.

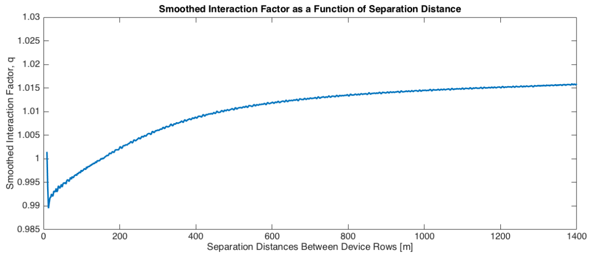

FIGURE 8: SMOOTHED INTERACTION FACTOR AS SEPARATION DISTANCE INCREASES

DISCUSSION

Examining the results, beginning with the 60 m x 60 m case, a separation distance similar to that found using the binary GA (shown in Figure 1) is found at about 30 meters, but a better solution is found at 51 meters. The reason that the binary GA doesn't find the solution at 51 meters is because of it's discretized nature. The arrangement shown in Figure 4, with an optimal distance of 51 meters, yields an increase in power of 3.34%.

Once the distance offshore is increased to search for a more optimal separation distance, this maximum interaction factor is found to yield a 4.03% power increase (as seen in Figure 5). When the rows are set as offset the results are found to be a very similar to those of the inline rows.

These results indicate that given two parallel lines of WECs in an array, the distance between these rows can yield up to a 4% increase in power, but that achieving such an increase is highly dependent on having optimal spacing between rows.

As the separation distance increases, the trend of the interaction factor, observed in Figure 8, demonstrates that, while the the optimal spacing distance occurs between 200 and 300 meters, placing the devices even farther apart results in interaction factors that are more robust, having a consistently higher average interaction factor. This consistent higher interaction factor is likely due to the positive interactions within the the two separate lines of WECs, and not connected to interactions between the two lines.

CONCLUSIONS

The wave energy industry is beginning to consider the placement of WEC arrays in the ocean and as such, it is important that prior to the physical implementation of these arrays, the many facets involved are considered and evaluated. One important determination is the configuration of devices within an array in that the layout will influence the developed power and the economics, in addition to having environmental and social impacts. The authors have previously introduced a novel algorithm for determining optimal WEC layouts, and as an extension of this work, a pattern was observed where arrays of WECs are formed with two parallel lines perpendicular to the oncoming waves. Further investigating this observation reveals that there are specific separation distances where the interaction factor (defined in Eq. 1) is maximized. However, slight variations around these optimal locations can readily result in interaction factors less than one. To achieve interaction factors that have a consistent average higher than one, the parallel lines must be adequately separated.

ACKNOWLEDGEMENTS

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