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Optimal Configuration and Tuning of Wave Energy Converter Arrays

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Link Foundation Fellowship Report, 2017-2018

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1 Narrative

1.1 Introduction

Power from ocean waves is becoming an increasingly attractive option as a source of renewable energy. Ocean waves are more reliable and predictable than sun and wind, and have a higher energy density [1]. There are locations where solar and wind energy would not be viable, due to the large amount of space they take up, either on land (solar) or above ground (wind). In addition, wave energy devices are less of a visual deterrent than wind turbines, and wave energy is particularly attractive for areas with a lot of coast line.

Wave energy is still in its infancy, though, and the state of the art is significantly behind that of wind and solar energy technology. There are no wave energy converters (WECs) that are grid-connected in the United States, and only a few megawatts worldwide [1]. For state-of-the-art WEC technologies, the price of energy is far too high to be economically viable. The U.S. Department of Energy held a competition in 2015 [2] to encourage progress in wave energy technology. Many companies and research groups showcased their ideas. The wide range of shapes and designs of different WECs proves that there is no consensus about what a WEC should look like. Additionally, there is no systematic approach to determine the "best" shape of a WEC. Therefore, the goals of our work are (1) to define the optimization problem, (2) to systematically and scientifically explain why one WEC is better or worse than another, and (3) to determine what the optimal WEC looks like.

1.2 Results

Our ultimate goal is to find the optimal shape of a general WEC. During this past year, our focus has been on obtaining a systematic approach to solving this problem. To achieve this, we limited our problem to a single-body three-dimensional axisymmetric point-absorber WEC, restricted to motion in heave with a linear power take-off (PTO) system in deep water with a single angle of propagation, assuming linear wave theory.

To define our optimization methodology, we need to determine a way to define any general axisymmetric body shape, calculate the extractable power from this shape, and establish what makes the optimal shape. We use polynomial basis functions to describe body geometries, so that we only need to change a few parameters (the coefficients of the polynomial basis functions) in order to produce a large number of different geometries. The shapes are then discretized, and relevant hydrodynamic properties are evaluated using the linear panel method WAMIT.

The measure of success for a wave energy converter is the capture width W, which is the ratio of the power extractable by the WEC to the power available in a sea state, per incoming crest length, or equivalently the length of incoming crest length from which the WEC extracts all energy. The theoretical maximum of W is $1/k$, where k is the wavenumber.

To begin our systematic search for the best shape, we first considered a hemisphere, since it is fully described by one parameter: the radius R. We found that for an incoming single-frequency wave with wavenumber k, there is one particular value of R that gives $W = 1/k$. This corresponds to the value of R that puts the body in resonance with the incoming wave.

Next we increased the number of parameters to two by looking at a cylinder, and varying radius R and draft H. For a range of R values, there are corresponding H values that put the body in resonance, resulting in the maximum capture width, $W = 1/k$. However, for some of these bodies to achieve resonance, and consequently the maximum capture width, it would necessitate the body moving an unrealistic amount. Therefore, we found that it is necessary to introduce a motion constraint to our problem, which limits the range of R and H pairs further. To differentiate which (R, H) pairs are better than others, we realized that some of the bodies have larger surface areas, and consequently higher costs, which introduces a second piece to our optimization problem.

Thus, our problem can be summarized as a multi-objective optimization, maximizing W and minimizing wetted surface area, S_W, while constraining motion. The multi-objective optimization introduced a Pareto Front to the problem. Realizing that there will be a start-up cost associated with a WEC, we determined that the optimal shape, minimizing surface area, maximizing capture width, and constraining motion, would be the point where the Pareto Front hits $kW = 1$. This is shown in Figure 1, for the case where the body is constrained to move no more than the amplitude of the incoming wave. The circle shows the optimal shape.

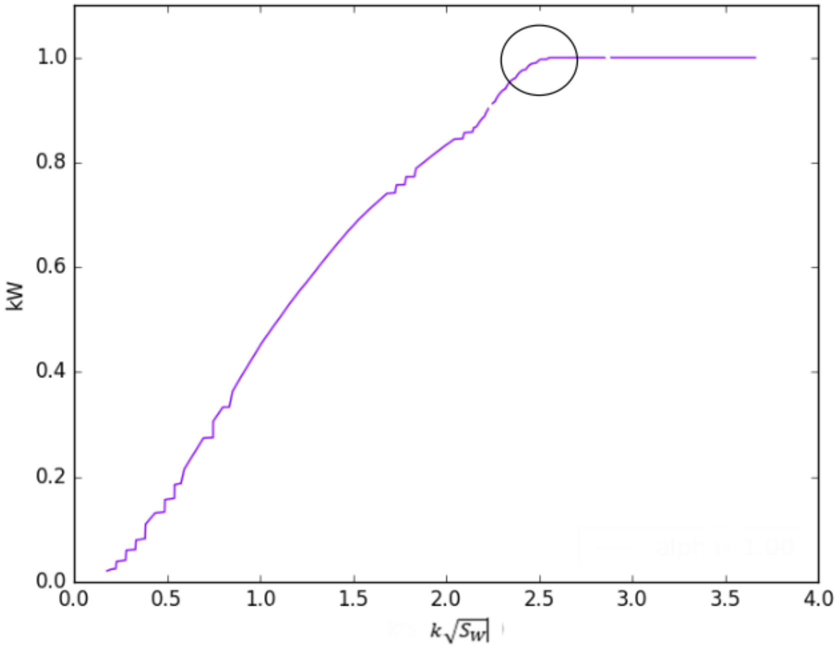

Figure 1: The Pareto Front for a cylinder, constraining the motion of the body to be no

more than the amplitude of the wave. This maximizes wavenumber k times capture width W while minimizing k times the square root of the wetted surface area of the body, S_W.

We compared the cylinder to a cone, also varying the radius and draft. We found that for a given motion constraint, the cylinder is preferable, since we can achieve maximum extractable power for a smaller surface area. Both the cylinder and cone achieve maximum capture width with smaller surface areas than the hemisphere. This gives us reason to believe that varying the shape more, by varying the coefficients of polynomial basis functions, will allow us to achieve maximum extractable power for even smaller surface areas for a given motion constraint.

1.3 Significance and Impact

There are many varying shapes and ideas for a WEC, but no general consensus, and more importantly there is no systematic study of how to determine the optimal geometry of a WEC. We have developed a framework that incorporates an easy way to consider many different shapes, a complete hydrodynamic analysis, and practical constraints such as limiting motion and minimizing cost to evaluate and analyze the performance of different floating bodies. This novel framework will be used to determine the general (non-axisymmetric) best shape for heave, then generalize to six degrees of freedom. We will also use it to investigate the effect of seastate spectrum. In general, it will improve the understanding of wave energy and wave-body interaction and could significantly increase the efficiency and cost-effectiveness of wave energy.

1.4 Where might this lead?

As mentioned above, the framework outlined here will next be applied to more general problems, including general axisymmetric shapes, non-axisymmetric shapes, surge, pitch, and 6 degree-of-freedom motion, as well as typical seastate spectrum. Further, we will use the insights gathered and framework developed on arrays of wave energy converters with controls.

2 Journal papers

I plan to submit a journal article to the Journal of Fluid Mechanics within the next few months, summarizing my findings from this year.

3 How did the Fellowship make a difference?

Being awarded the Link Foundation Ocean Engineering and Instrumentation Fellowship has enriched my academic experience by allowing me to continue spending the majority of my time doing research and enhancing my knowledge. In addition, the prestige of the award will no doubt enhance my future career options. I am extremely grateful to have been chosen for this award and would like to extend my sincerest gratitude towards everyone at the Foundation.

References

[1] Lehmann M, Karimpour F, Goudey CA, Jacobson PT, Alam MR. 2017. Ocean wave energy in the United States: Current status and future perspectives. Renewable and Sustainable Energy Reviews 74: 1300-1313.

[2] Wave Energy Prize. U.S. Department of Energy. https://waveenergyprize.org/