HEURISTIC OPTIMIZATION METHODS APPLIED TO WAVE ENERGY: MINIWEC FLOAT SHAPE CASE STUDY

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INTRODUCTION

Ocean waves are an abundant resource which, when harnessed by wave energy converters, can be readily used in a variety of power applications. Though modern wave energy research began in the 1970s, there is still much variation in wave energy converter (WEC) design, even across onshore, nearshore, and offshore operational domains [1]. This research presents a case study of a heuristic optimization method applied to an existing WEC design relative to a specific wave climate.

Heuristic optimization methods are faster and more cost effective than direct methods which solve through a finite sequence of operations. Heuristic methods converge towards the global optimal solution [2]. This study focuses on the University of Washington's (UW) Applied Physics Lab's (APL) miniWEC wave energy converter platform as a case study, optimizing the float shape for annual average power in Lake Washington. However, our broader research objective is to demonstrate a frequency-domain-based, computationally cost-effective optimization approach to hydrodynamic WEC optimization.

BACKGROUND

Since the Salter Duck [6], there have been and continue to be a wide variety of WEC float designs of all shapes and sizes. Recently, a number of studies have shown promise in the optimization of WEC geometry using heuristic methods in the frequency-domain. McCabe [7] used a genetic algorithm to optimize the shape of a WEC that moves in surge. The frequency-domain code WAMIT was used for analysis [8]. This optimization approach considered size, shape complexity, and performance of candidate solutions. Garcia Teruel et al. [9] continues this research with a multi-objective geometry optimization; optimizing hydrodynamic performance and minimizing the levelized cost of energy of a WEC. This research includes 3D geometry and analysis in the frequency-domain, with plans to also optimize in the time-domain. The geometry of an oscillating water column was optimized in the frequency-domain using WAMIT by Gomes et al [10].

Different types of WECs have also been optimized in the time-domain. Babarit et al [11] used a genetic algorithm to optimize the shape and mechanical parameters of a floating WEC with control in the time-domain. Bailey et al [12] optimized the shape of a buoyant pontoon WEC at different sites globally using time-domain analysis. The paper demonstrated that the optimal shape is dependent on the wave climate. Ortiz et al [13] optimized the shape of a two-body point absorber WEC mooring system. A high-fidelity time-domain model was used in a pre-processing stage to cover a larger design space.

Heuristic optimization methods can be applied to other aspects of WEC optimization beyond single device geometry optimization. Mundon [15] used a genetic algorithm to optimize the control parameters for an attenuator WEC using neurobiological exemplars. Gunn et al. [16] also use genetic algorithms to optimize a WEC control strategy. Sharp et al. [17] used a genetic algorithm to optimize the array layout of five WECs.

MINIWEC

A heuristic optimization will be the primary method applied in this study. The miniWEC is a two-body point absorber developed by the APL at the UW. The present float shape was chosen due to convenience and availability, and it is clear that this geometry is suboptimal with regards to hydrodynamic performance of the device. Figure 1 shows that the surface float is a cylinder with a diameter of 1.83 m and height of 0.81 m, producing power from vertical/heave motion, relative to a heave-plate suspended below the float by a tether connected to a power take-off unit atop the float.

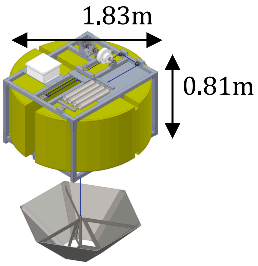

FIGURE 1. MINIWEC TWO-BODY POINT ABSORBER DEVELOPED BY THE APPLIED PHYSICS LAB [3]

Lake Washington Wave Climate

The APL uses the miniWEC for testing of WEC technologies in Lake Washington, where the significant wave height and dominant period of typical Lake Washington waves serve as an approximately 1:7 testbed for open-ocean deployments of full-scale WECs .

Data gathered in Lake Washington is presented in Figures 2 and 3. Waverider data was collected in 30-minute intervals from Oct 26, 2011 to Jan 11, 2012 [3]. The data was binned by wave period (T_P) and wave height (H_S) to calculate a joint probability distribution [4]. Figure 2 presents the bulk of the wave energy observed in the lake, which were used in the analysis.

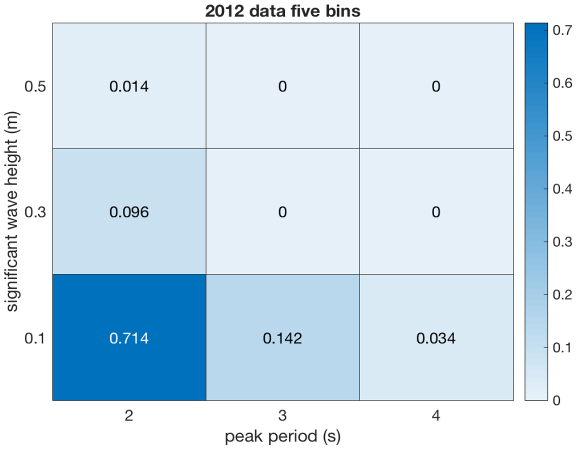

FIGURE 2 – JOINT PROBABILITY DISTRIBUTION LAKE WASHINGTON

A JONSWAP spectrum is found to best describe the wave energy observed with gamma between 2.5 and 3.3 [5]. The energy spectra from the 30-minute intervals were plotted for the five wave cases to estimate the value of gamma. Smaller amplitude bins with Hs of 0.1m fit well with the 3.3 value of gamma, while the larger amplitude bins fit better with a gamma value of 2.5 (Figure 3).

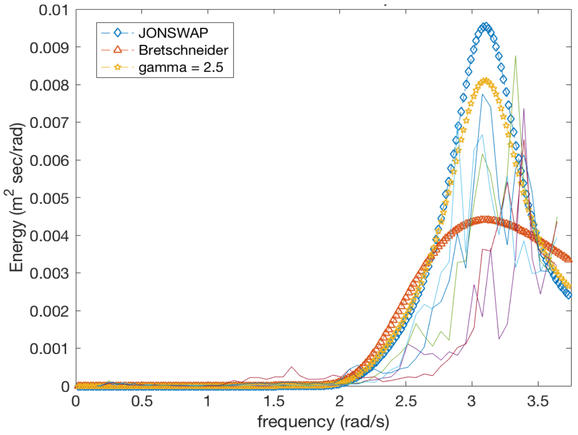

FIGURE 3 - ESTIMATING GAMMA FOR LAKE WASHINGTON SPECTRA, 0.3$_M$ H$_S$, 2$_S$ T$_P$ WAVE CASE

WAVE ENERGY THEORY

Linear wave theory is applied assuming relatively small waves compared with the size of a WEC [18]. Equation 1 shows the equation of motion of a heaving point absorber for mass, *m,* and displacement, $X_{(t)}$ [19-20]. The total force, $F_{T(t)}$, has components of fluid-induced forces, $F_{F(t)}$, and external forces, $F_{EXT(X,\dot{X},t)}$. Equation 2 shows that the fluid-induced forces, $F_{F(t)}$, can be approximated by the sum of the exciting, radiating, and hydrostatic forces: $F_{S(t)}$, $F_{R(t)}$, and $F_{H(t)}$, respectively.

$$m\ddot{X} = F_{T(t)} + F_{EXT(X,\dot{X},t)} \tag{1}$$

$$F_{F(t)} = F_{S(t)} + F_{R(t)} + F_{H(t)} \tag{2}$$

METHODOLOGY

A genetic algorithm (GA) is employed to optimize the miniWEC float geometry, wherein the axisymmetric float is represented with 2D geometry and fitness is assessed using the frequency-domain response. The 2D profile represents a slice of the 3D axisymmetric shape that is rotated about the vertical axis. This is a computationally effective way to store the data for the individual shapes. Figure 4 shows the 2D genetic representation of the float profile and corresponding mesh using the open source boundary element method (BEM) tool NEMOH for a random shape [21]. Minimum radius bounds are set at the existing outer diameter (0.91m) and the maximum radius is set as to be deployable by the existing research vessel (1.22m) used in deployment and recovery. The radius is allowed to vary at 26 equally spaced points between the top and base of the float, set at the existing miniWEC float height of 0.81m.

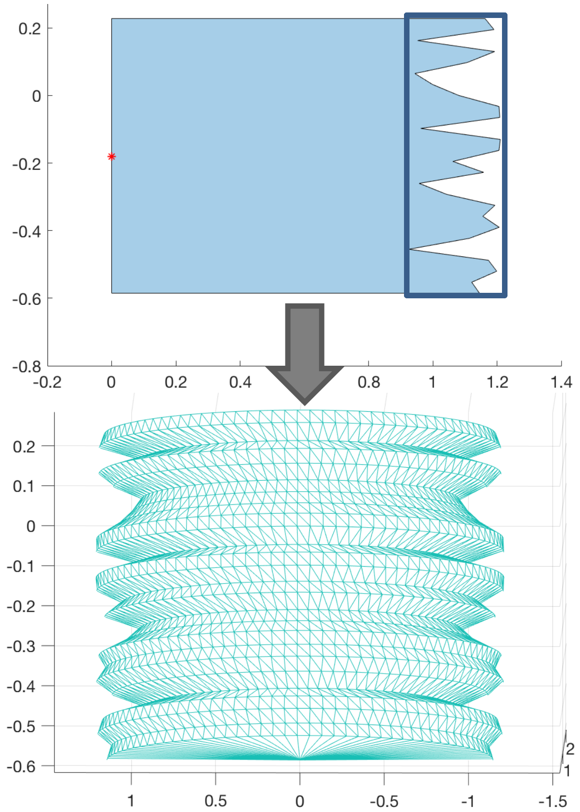

FIGURE 4 - 2D PROFILE TO 3D NEMOH MESH

The goal is to optimize the miniWEC float shape for annual average power in Lake Washington. The mean power for the five wave cases multiplied for the probability of occurrence for each bin (Figure 2) provides the annual average power for each float shape. The available Lake Washington data only includes the winter months, but it is assumed to be representative of the year for this analysis.

Using the time-domain analysis for each individual would be time consuming and computationally expensive [22]. Therefore, the frequency-domain NEMOH code is used exclusively within the GA [21]. A power proxy is used for the fitness function within the GA which ranks the relative annual average power based on frequency-domain response. In order to develop an acceptable proxy for power, a number of reference float shapes are generated and evaluated. This preliminary float shape analysis provides a benchmark to compare frequency-domain and time-domain data to test the fitness function.

Preliminary Float Shape Analysis

Ten preliminary float shapes are analyzed using NEMOH and ProteusDS. The draft for each is set so that all shapes have an equivalent submerged volume. The shapes are meshed using Rhino to include non-linear buoyancy in the time-domain. The five dominant Lake Washington wave cases (Figure 2) are run using JONSWAP waves in ProteusDS. Viscous drag is added to the base of each of the floats. The average annual power for each shape is estimated from the PTO tether velocity and weighted by the joint probability distribution. Figure 5 shows power for all shapes compared to the baseline cylinder.

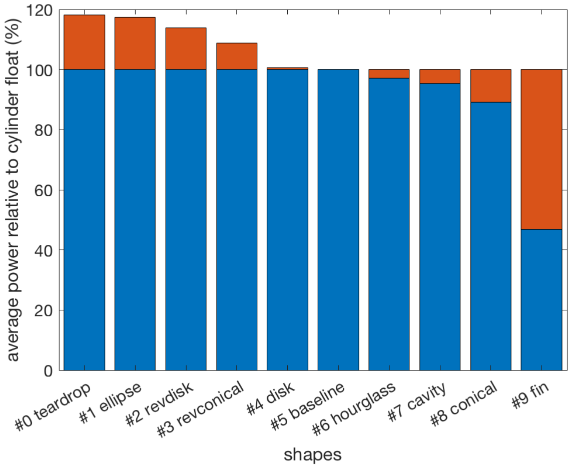

FIGURE 5 – AVERAGE POWER RELATIVE TO CYLINDER FOR PRELIMINARY FLOAT SHAPES

Comparing the annual average power from the time-domain analysis with the hydrodynamic coefficients from the frequency-domain analysis tests the method for ranking the power proxy in the frequency-domain. This is accomplished through a weighted multi-objective function inclusive of heave excitation, heave damping, and heave added mass. WEC motions not in heave are represented in constraints.

Genetic Algorithm

The genetic algorithm is composed of code from the University of Sheffield's GA toolbox [23]. This toolbox is compatible with MATLAB and provides adaptable tools for implementing GAs. An initial population of 30 individuals is used. There is 10% elitism which allows the three best performing individuals to be cloned to the next generation. The top 24 individuals are the parents, resulting in a 20% kill rate. The parents form 12 pairs and produce two offspring each. This results in 24 offspring from crossover. The remaining three individuals are created randomly to enhance genetic diversity, which increases the chance of converging to the global optimal solution [2]. Mutation rate also influences genetic diversity, and a mutation rate of 1% allows 8 decision variables to be mutated (decision variables include 30 individuals with 26 points each). The selected precision allows increments of 0.01m spacing between the minimum and maximum radii, resulting in 6×10^{38} possible shape solutions.

The initial population is seeded with the four highest power producing shapes from the preliminary shape analysis, and otherwise created randomly. The shapes are ranked using the objective function. These results are archived to keep the decision variables and corresponding objective evaluation for repeated shapes. Additionally, a list of the best performing individuals is separately stored and updated with the best solutions from all generations. The process continues until convergence is reached over many generations, the specified maximum number of generations has been reached, or there is no improvement over many generations.

The GA is used to find an optimal axisymmetric miniWEC float shape. The generated float shape is analyzed in ProteusDS to estimate the power increase as compared to the baseline cylinder float.

RESULTS AND DISCUSSION

Work is presently ongoing in developing and evaluating an optimized float geometry, however, the frequency-domain analysis within the GA, can be seen to provide orders of magnitude computational efficiency over a time-domain approach. While frequency-domain analysis within heuristic optimization has been used in other studies, the authors are not aware of another study that has created a power proxy using only frequency-domain analysis. Time-domain analysis of the final shape post GA quantifies the significant increase in the annual average power as compared with the original cylinder miniWEC float.

This case study showcases a methodology for heuristic float shape optimization, demonstrating computationally efficient frequency-domain evaluation of hydrodynamic performance within a GA. Favorable results indicate potential for more complex 3D shapes deployed in more complicated wave climates. Additionally, the objective function which is based on preliminary float shape analysis could be further refined using a machine learning approach. Many more float shapes could be evaluated in the time-domain and frequency-domain, and a GA could evaluate the best power proxy.

The final float shape will be added to the existing miniWEC, (with no material removed from the existing device), and field tested in Lake Washington to verify anticipated annual average power gains relative to previous deployments. Alternatively, small-scale tank testing can also provide validation.

CONCLUSIONS

Heuristic optimization methods can provide substantial contributions as future WECs continue to evolve and converge to subsets of designs. Heuristic optimization methods show promising results thus far in facilitating this design advancement. This research study developed a proxy between time-domain analysis of power using ProteusDS with the open source NEMOH hydrodynamic coefficients. More complicated shapes, varied wave environments, and advancement of the objective function can be developed further through future work. Final construction and field testing or small-scale tank testing will validate the power increase between the original miniWEC cylinder and the optimal float shape obtained through the GA. Ideally, this method will provide knowledge to the heuristic optimization research space and contribute towards design convergence of subsets of WECs.

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