Array Design and Device Damping Assignment of Fixed Oscillating Water Columns

Chris Sharp*
Oregon State University
Corvallis, OR, USA

Bryony DuPont
Oregon State University
Corvallis, OR, USA

Bret Bosma
Oregon State University
Corvallis, OR, USA

Pedro Lomonaco
Oregon State University
Corvallis, OR, USA

Belinda Batten
Oregon State University
Corvallis, OR, USA

*Corresponding author: sharpc@oregonstate.edu

1. INTRODUCTION

As the wave energy industry advances towards full scale deployment, researchers are exploring how to achieve maximum array power generation and interaction factor (also referred to as q-factor and is defined in Equ. (1)) [1].

$$q = \frac{P_{array}}{N * P_i} \tag{1}$$

While the physical phenomena that affect power development are currently being studied, both array optimization and active device control have theoretically shown substantial benefits to array power development [2, 3, 4]. Despite these individual efforts, the potential impact of *combined* array optimization and active control have yet to be explored. As a component of the Department of Energy's Advanced Laboratory and Field Arrays (ALFA) project, we are performing an initial study regarding how to best jointly consider array optimization and active device control.

We propose a segmented research approach where we explore different combinations of array optimization and controls optimization scenarios, such that we can identify and isolate the impacts of each of these contributions to array power development. This research lays the groundwork for future integration of active control into array optimization algorithms.

To best understand the impact of array optimization with optimal, device-specific damping, we consider three case studies. These include fixed layouts with a fixed array damping (Case 1), fixed layouts with optimized device-specific damping (Case 2), and optimized layouts with a fixed array damping (Case 3). We opted not to consider optimized layouts with optimized WEC-specific damping due to minuscule improvements in power and computational expense. For the cases with fixed layouts, the layouts are informed by existing research. For the cases with fixed damping, these values are obtained by determining the optimal damping value of a single device in isolation. Figure 1 shows the relationship between these case studies.

		Device Specific Damping	
		Optimized	*Not Optimized*
Layout	*Optimized*	−−	Case 3
	Not Optimized	Case 2	Case 1

Figure 1: Overview of cases being considered.

In this paper we will briefly describe our array optimization method, our device damping value optimization method, and the results we have obtained thus far for the different cases.

2. METHODOLOGY

The devices we are considering in this project are oscillating water columns and are further described in Bosma et. al. [5]. We chose to construct and utilize these devices because they are inexpensive, enabling the development of five devices to be used for tank testing and validation. Additionally, the design of these devices allows for more manageable controllability because the electronic hardware is out of water.

As a preliminary step in all three of these case studies, we model our chosen device as a heaving point absorber using the boundary element modeling software WAMIT

[6]. We chose to model the device using the piston approach based on existing research [7, 8, 9]. The output of WAMIT will be directly applied as part of the optimization process through the use of the array power calculation software, *mwave* [10]. *Mwave* is required to analytically determine an array's power in a computationally efficient manner such that device-to-device wave interactions are considered. More information on incorporating *mwave* into the optimization process can be found in our previous work [11, 2, 3].

2.1 Device Damping Assignment

After modeling our device in WAMIT, we then determine an optimized damping value for a single device. This value will be used throughout Cases 1 and 3 and as an initial starting value for Case 2. The optimized damping values are highly dependent on the sea state experienced by the device. In this work, we are considering the four sea states shown in Table 1.

In the *mwave* power development code, the damping value of the wave energy converter is a tunable parameter. Our previous work treated this value as a constant, utilizing the value given by Child & Venugopal [12]. In order to obtain an optimal damping value for our device, we implemented a Golden Section search to determine the optimal damping value that results in the highest power development. We observed that for a single device in a set wave field, there is one distinct maximum. The optimal values for damping are shown in Table 1.

Table 1: Evaluated Sea States and Associated Single WEC Optimal Damping.

Sea State	Hs [m]	Tp [s]	damping [kg/s]
A	0.136	1.91	**174.82**
B	0.136	2.26	**318.93**
C	0.139	2.48	**428.01**
D	0.242	3.30	**818.46**

2.2 Array Design

Depending on the case being evaluated, the array's layout may be either predefined (Cases 1 & 2) or found using our problem-specific optimization scheme (Case 3).

2.2.1 Predefined Layouts

To choose the predefined layouts for evaluation, we selected a set of 11 potential layouts from existing literature [13, 14, 15]. From these 11 layouts, four were ultimately selected for in-depth evaluation in Cases 1 and 2. These four layouts are shown in Figure 2 and were selected based on their performance and their prevalence in existing research. 'n' is a separation distance scaling factor and 'Dia' is the diameter of the devices (0.62 meters). This separation distance is measured from center to center of the devices.

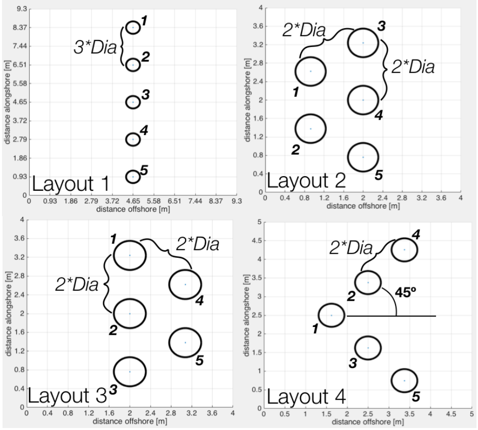

Figure 2: Predetermined Layouts for Cases 1/2

2.2.2 Optimized Layouts

To find the optimal layouts for Case 3, we utilized the problem-specific genetic algorithm we have developed and discussed in our existing work [2]. The methodology for Case 3 is presented in depth in Sharp et. al. [3]. This algorithm has been developed further to include device-specific damping optimization within the objective evaluation; however the small improvement in power and interaction factor was not worth the computation time needed – primarily because of the need to generate results promptly for tank testing.

3. RESULTS

In this section, we show the results we have obtained thus far from our work investigating the three different cases.

3.1 Case 1: Fixed Layouts with Fixed Damping

In Case 1, the four fixed layouts from Figure 2 are evaluated with one fixed damping value for all devices (shown in Table 1).

3.2 Case 2: Fixed Layouts with Optimized Damping

Case 2 uses the same predetermined layouts as Case 1; however, instead of a single damping value used for all devices, optimized damping values are found for each individual device. To determine these values, a Golden Section search is again used. For the search, the damping values from Table 1 are used as initial values and the search intervals used when determining these initial values are used as initial search intervals for the device–specific search.

The optimal damping for each device is sought so that all the damping values except for one are fixed. Searching iteratively through all the devices in the array the device specific optimums are settled on when the overall objective function no longer changes. To ensure that the global optimal damping values are found, the devices are iteratively searched through in a random order.

Table 2: Case 1 Results

Layout 1	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	14.114	13.913	14.310	40.339
q-factor	1.1030	1.0643	1.0505	1.0231
Layout 2	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	13.053	13.640	14.184	39.682
q-factor	1.0200	1.0434	1.0413	1.0065
Layout 3	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	12.804	13.526	14.122	39.697
q-factor	1.0006	1.0347	1.0368	1.0069
Layout 4	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	12.505	13.125	13.778	39.691
q-factor	0.9773	1.0039	1.0115	1.0067

Table 3: Case 2 Results

Layout 1	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	14.129	13.915	14.310	40.3410
q-factor	1.1042	1.0644	1.0506	1.0232
Layout 2	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	13.181	13.686	14.225	39.797
q-factor	1.0300	1.0469	1.0443	1.0094
Layout 3	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	12.895	13.529	14.183	39.814
q-factor	1.0078	1.0397	1.0412	1.0098
Layout 4	(from Fig. 2)			
Sea State	A	B	C	D
Power [W]	12.546	13.157	13.803	39.736
q-factor	0.9805	1.0064	1.0133	1.0079

3.3 Case 3: Optimized Layouts with Fixed Damping

This case is similar, and based on, our previously presented work [3]. Utilizing a fixed damping value for all the devices within the array, this informed value is dependent on a single WEC's behavior in a given sea state and is shown in Table 1. Each sea state yields a unique layout and power output as shown in Fig. 3. These layouts, while similar in appearance to Layout 1 of the fixed layouts, these optimal configurations do differ slightly in the spacing between devices. The power and interaction factors associated with each of these layouts can be found in Table 4

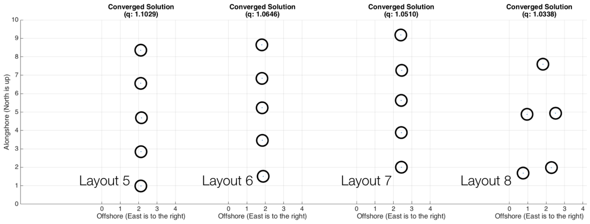

Figure 3: Optimized Layouts for Case 3

Table 4: Case 3 Results

Sea State	A	B	C	D
Layout	5	6	7	8
Power [W]	14.113	13.917	14.316	40.7570
q-factor	1.1029	1.0646	1.0510	1.0338

4. OBSERVATIONS

There are several observations worth noting from the initial results. Primarily how the interaction factors, damping values and layout designs are effected across the different cases.

4.1 Interaction Factor

We observe that when comparing across sea states an increase in power does not necessarily correspond to an increase in interaction factor. This indicates that device geometry and experienced sea state may correlate more directly to power development rather than to interaction factor. However, the ability to achieve larger interaction factors in sea states which may be less conducive to power development is an indicator of the importance of layout optimization. Meaning that even if a layout experiences a sea state for which the individual devices are not well–designed, a layout can be found with can yield relative increases in power.

4.2 Damping

We also note that generating device specific damping values does produce improvements in power development and interaction factor. This is shown when examining Cases 1 and 2. However, the improvements are relatively minor. These changes are likely small because the values are tuned to a sea state and a layout and do not consider the individual waves that are experienced. This indicates a further need to include active control scenarios in future array optimization development.

4.3 Layout Design

Lastly, when we compare the behavior of predetermined layouts with optimized layouts, we see that incorporating layout optimization yields better power production across all the considered sea states. Furthermore, the power produced across the sea states are more consistent (seen in Case 3) when the layouts are optimized than when they are fixed (Cases 1 and 2).

5. CONCLUSIONS

The goal of this work is to better understand the connection between layout design and device damping adjustment. Eventually, layout optimization methods should include active control in order to provide better informed layout options. To explore the potential influence of active control in array optimization, we have examined three distinct cases that include fixed/optimized layouts and fixed/optimized device-specific damping. These results provide a great base to further explore active control in conjunction with layout optimization.

6. ACKNOWLEDGEMENTS

This paper is based upon work supported by the United States Department of Energy under Award Number DE-EE0006816. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or (a) implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe upon privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

7. REFERENCES

[1] Ferri, F., 2017. “Benchmark of optimisation algorithms for wecs arrays”. In Proceedings of the Twelfth European Wave and Tidal Energy Conference, A. Lewis, ed., EWTEC, pp. 798-1–798-7. ISSN: 2309-1983.

[2] Sharp, C., and DuPont, B., 2016. “A Multi-Objective, Real-Coded Genetic Algorithm Method for Wave Energy Converter Array Optimization”. In ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, pp. 1–10.

[3] Sharp, C., DuPont, B., Bosma, B., Lomonaco, P., and Batten, B., 2017. “Array optimization of fixed oscillating water columns for active device control”. In Proceedings of the Twelfth European Wave and Tidal Energy Conference, A. Lewis, ed., EWTEC, pp. 1016-1–1016-10. ISSN: 2309-1983.

[4] Giassi, M., GÃűteman, M., Thomas, S., EngstrÃűm, J., Eriksson, M., and Isberg, J., 2017. “Multi-parameter optimization of hybrid arrays of point absorber wave energy converters”. In Proceedings of the Twelfth European Wave and Tidal Energy Conference, A. Lewis, ed., EWTEC, pp. 682-1–682-6. ISSN: 2309-1983.

[5] Bosma, B., Brekken, T., Lomonaco, P., McKee, A., Paasch, B., and Batten, B., 2017. “Physical Model Testing and System Identification of a Cylindrical OWC Device”. *12th European Wave and Tidal Energy Conference [accepted].*

[6] WAMIT Inc., 2016. “WAMIT V7.2 User Manual”. WAMIT Inc.

[7] Penalba, M., and Ringwood, J. V., 2016. “A review of wave-to-wire models for wave energy converters”. *Energies,* ***9***(7).

[8] Kelly, T., Dooley, T., Campbell, J., and Ringwood, J. V., 2013. “Comparison of the experimental and numerical results of modelling a 32-oscillatingwater column (OWC), V-shaped floating wave energy converter”. *Energies,* ***6***(8), pp. 4045–4077.

[9] Simonetti, I., Cappietti, L., El Safti, H., and Oumeraci, H., 2015. “Numerical Modelling of Fixed Oscillating Water Column Wave Energy Conversion Devices: Toward Geometry Hydraulic Optimization”. *Volume 9: Ocean Renewable Energy,* ***9***, p. V009T09A031.

[10] McNatt, J. C., Venugopal, V., and Forehand, D., 2014. “A novel method for deriving the diffraction transfer matrix and its application to multi-body interactions in water waves”. *Ocean Engineering,* ***94***, pp. 173–185.

[11] Sharp, C., and DuPont, B., 2015. “Wave Energy Converter Array Optimization – A Review of Current Work and Preliminary Results of a Genetic Algorithm Approach Introducing Cost Factors”. In ASME 2015 International Design Engineering Technical Conference & Computers and Information in Engineering Conference, ASME, pp. 1–10.

[12] Child, B. F. M., and Venugopal, V. “Modification of power characteristics in an array of floating wave energy devices”. In 8th European Wave and Tidal Energy Conference.

[13] Miguel, B. D., Ricci, P., Touzón, I., and Ojanguren, M., 2012. “New perspectives on the long term feasibility of wave energy conversion : a techno-economical approach”. In ICOE, pp. 1–7.

[14] AndrÃl’s, A. D. D., Guanche, R., Meneses, L., Vidal, C., and Losada, I. J., 2014. “Factors that influence array layout on wave energy farms”. *Ocean Engineering,* ***82***, pp. 32–41.

[15] Myers, L., Bahaj, A. S., Retzler, C., Ricci, P., and Dhedin, J.-f. “Inter-device spacing issues within wave and tidal energy converter arrays”. In 3rd International Conference on Ocean Energy, pp. 1–6.