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Layout design of wave energy parks by a genetic algorithm

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ABSTRACT

If wave energy systems are to become a viable option competitive with more mature renewable energy sources, the systems must be optimized with respect to maximal electricity production and minimized costs. The number of parameters involved in large-scale wave energy systems is typically too large for traditional optimization methods to be feasible, and the solution space may contain many local minima. Here, an optimization tool for application in wave energy design based on a genetic algorithm is presented. The internal parameters of single point-absorbing wave energy converters (buoy radius, draft and generator damping) are optimized and the results validated against parameters sweep optimization. Further, since the individual devices in a park affect each other by scattered and radiated waves propagating in all directions, the tool is used to find the optimal spatial layout of parks. Arrays with different number of devices are studied and similar optimal layouts appear in all cases, which allows extrapolation of the results to even larger parks. The results show that the tool is effective in finding layouts that avoid destructive interactions and get a q-factor slightly above 1.

1. Introduction

Wave energy is a clean and renewable energy source that has the potential of contributing to 10% of the world's electricity consumption (Clément et al., 2002), or as much as 17% in some countries such as UK (BERR, 2008). However, in order to become economically feasible, the efficiency of the wave energy technology must improve. To produce electricity in the MW range, wave energy converters (WECs) must usually be deployed in large arrays, or parks. In particular, this is true for small point absorber devices.

The WECs will interact hydrodynamically by scattered and radiated waves, which may affect the total power production positively or destructively, and the total performance of the park will be affected by many different parameters, for example the number of devices, their separation distance and individual dimensions, the geometry of the park and the wave climate. The increase in power production and reduction in power fluctuations as functions of the number of devices in a park was studied by Tissandier et al. (2008); Vicente et al. (2013); Engström et al. (2013) and Göteman et al. (2014) and the effect on the park performance of the separating distance between devices has been studied by Ricci et al. (2007); Borgarino et al. (2012) and Göteman et al. (2015b). The global geometry can have a large effect on the output power and the fluctuations in an array. Child et al. (2011) showed that certain array layouts can increase the power with 5% or lead to a decrease of up to 30%.

Most studies on designing optimal wave energy parks have been based on comparisons of a few different configurations (Babarit, 2013; Bozzi et al., 2017). A more systematic approach is to use an optimization scheme such as a genetic algorithm (GA). Genetic algorithms originate from theory of evolution studies, but have since been applied in a variety of areas, ranging from string theory (Blåbäck et al., 2014) to pharmaceutical research (Jones et al., 1997). The algorithm mimics the process of natural selection and incorporates inheritance, mutation and selection among states in the solution space to find global minima of stated problems.

A few works on array layout optimization using a genetic algorithm approach have been presented by Child and Venugopal (2010); Child (2011); Child et al. (2011); Sharp and DuPont (2016) and Giassi and Göteman (2017). They deal with the problem of optimization of arrays of point-absorber WECs in terms of spatial layout or of power take off characteristics. Child and Venugopal (2010) and Child (2011) used two optimization methods: parabolic intersection and genetic algorithm. By means of these two approaches the spatial configuration of 5 identical devices upon power output of the array was optimized with different kind of tuning of the devices. In their study, the MATLAB GA and Direct Search Toolbox was used. Another model to determine array configurations, where the evaluation function contained power output and costs, was presented by Sharp and DuPont (2016), with binary and continuous GA. Both optimizations of power take off characteristics, given a fixed

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layout, and of array layout of 10 identical WECs, given fixed power take off coefficients, were included in the work by Child et al. (2011).

The mentioned works all shed important insight into optimal configurations of wave energy parks, but approximations and model differences imply that no generic conclusions can be drawn on optimal wave energy parks.

The objective of this study is to develop and use a new optimization tool for arrays of point absorber wave energy converters which can be used as a reliable and fast pre-deployment evaluation method, where the motion and power of each device is computed in the time domain and the input is irregular waves.

Differently from the previous studies, the present work first studies full optimization of the design variables of a single point absorber device, i.e. the simultaneous search of the best geometry of the floater and the best PTO setting for a given sea states. Secondly, the comparison with a parameter sweep (PS) optimization of the single device, has allowed validation of the GA method and evaluation of its accuracy. Furthermore, regarding the array layout optimization, two different GA models have been created from scratch: discrete and continuous variables optimization of arrays up to a customizable number of fully hydrodynamically interacting WECs. A comparison between these two approaches has been carried out. The influence of the variation in the number of devices (from 4 to 14 WECs) within the same constrained space has been also addressed. The power production of the devices is calculated in the time domain and no resonance condition is assumed as in Sharp and DuPont (2016). The crossover method implemented is different from Child and Venugopal (2010) but similar to the one in Sharp and DuPont (2016), as described in more detail in section 2.

The semi-analytical hydrodynamic model used to compute the interactions among the devices is suitable for axisymmetric cylindrical floaters and it has been used here with point absorbers buoys. However, the genetic algorithm layout optimization routine implemented can potentially be applied to arrays of different devices (in geometry and working principle), provided that a suitable interactions model is included.

The paper is organized as follows: the genetic algorithm model and parameters setting are outlined in section 2. The description includes the different variations for a single WEC and for the array. In section 3, results of the optimization are presented, and further discussed in section 4. Conclusions are drawn in section 5.

2. Method

2.1. Genetic algorithm

Evolutionary algorithms are specific metaheuristic optimization algorithms which base their procedure and nomenclature on the theory of biological microevolution of living being. The genetic algorithm is one of these methods, developed by Holland (1975); the optimization is performed by implementing and iterating a "genetic evolution" over a set of solutions, until sufficiently good results are obtained. These methods rely on an intelligent search of a large but finite solution space using statistical methods and can deal with discrete variables and non-continuous cost functions (Haupt and Haupt, 2004). In fact, in optimization problems of energy converters arrays, a large parameter space is involved (making parameter sweep infeasible) and the shape of the cost function is not known and probably multi-peaked (Child and Venugopal, 2010). Therefore, a genetic algorithm method is well suited for the problem.

In this study three slightly different GAs were developed and implemented in the MATLAB programming language. The algorithms were coded from scratch based on the theory described in Haupt and Haupt (2004), and are described in details later in this section. In this paper we deal with the following optimization cases:

- Single device: optimization of the internal hydrodynamic parameters such as buoy radius, draft and generator damping coefficient of a single point absorber WEC of the type developed at Uppsala University (Leijon et al., 2009).
- Array code A: optimization of the spatial coordinates of an array of identical devices where the possible coordinates (solutions) are random positions on a fixed regular grid.
- Array code B: optimization of the spatial coordinates of an array of identical devices where the possible coordinates (solutions) are continuous random numbers.

The single WEC genetic algorithm tool aims to find the optimal value of the radius (R) and draft (d) of the buoy and the damping coefficient (γ) of the generator, considering the point-absorber WEC similar to the one developed at Uppsala University (Fig. 1). It consists of a linear generator located at the seabed and a floating buoy at the surface, connected by a connection line. The linear generator is composed by a moving part (translator) with permanent magnets and a static part (stator) with coil windings. As the incoming waves reach the WEC, the buoy and the translator move upwards (wave crest) and downwards (wave through). The relative movement between the permanent magnets and the coils induces electricity. Further details about the converter can be found in Leijon et al. (2009).

For a given sea state, the single WEC GA method allows to find the size of the buoy and the PTO setting which gives the highest theoretical power production. The array optimization aims to find a layout geometry for a number of identical (in geometry and generator damping coefficient) WECs which improves the total power production.

Parameters settings. The genetic algorithm routine is based on the arbitrary choice of some parameters which can influence the achievement of convergence and the output results. Nomenclature is inspired by evolutionary theory. Here, parameters, terminology and notation used in the paper are presented.

The optimization process starts with the random creation of the first *population*, which is a set of a fixed number (*nPop*) of *chromosomes*. According to the variables involved in the optimization process, each chromosome contains a certain number (*Nvar*) of *genes* (*nGene*). Each *gene* represents a variable that will be optimized in the process. In the single WEC genetic algorithm the number of different genes (*nGene*) in every chromosome is three: R, d, γ, while for the array codes A and B the number of different genes (*nGene*) is equal to one (namely the couple of coordinates $[x_i, y_i]$, where i is the i-th device in the park). Therefore, in code A and B, there will be *Nb·nGene* genes (*Nvar*) in every chromosome, where Nb is the number of WECs in the array (see Fig. 4).

Initial population. The first *population* (or first set of chromosomes) is generated by uniform random sampling. It represents the first set of solutions from which the algorithm will start its optimization routine.

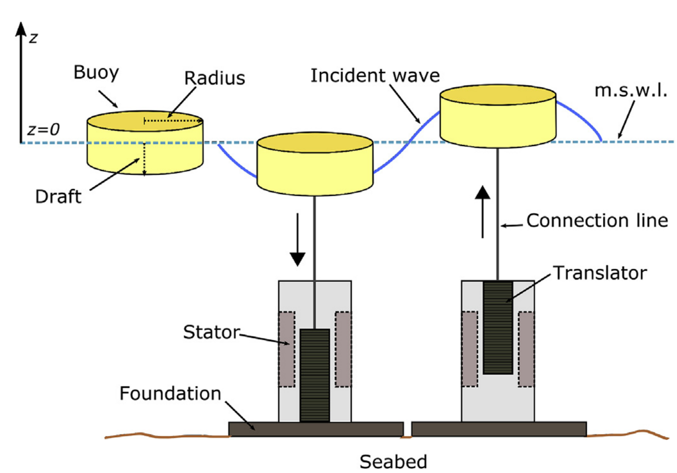

Fig. 1. Uppsala University wave energy converter concept. The dotted line indicate the mean surface water level (m.s.w.l).