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Multi-dimensional optimisation of Tidal Energy Converters array layouts considering geometric, economic and environmental constraints

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A study for the optimisation of in-stream tidal energy converter array layout for a three-dimensional fluid flow field is presented. The study involves design of experiments, computational fluid dynamics simulations, surrogate model construction, and constrained optimisation. Linear Radial Basis Functions (RBF) are used to build surrogate models as a function of four design variables: streamwise, spanwise, vertical and staggered spacings, with the purpose of approximating the capacity factor of an array with a fixed number of Tidal Energy Converters (TECs). Effects of arrays on maximum and minimum stream velocities at specific locations are also assessed. A constrained optimisation mathematical model is formulated considering geometric, economic and environmental aspects. Results are presented in terms of economic revenue for each optimisation model. The method proves to be very time efficient in the evaluation of numerous tidal energy convert array layouts with a view to satisfying optimality criteria.

1. Introduction

Technology Readiness Level (TRL) is a universally employed metric for the degree of development of a technology towards deployment. Normally, nine numerical values are assigned to the development of a technology, having values in the range 1–9, whereby the progress of a technology from basic research to system proof and readiness for full deployment is indicated in ascending order of the numerical values of the TRL [1]. TRL has been widely applied in energy technology development; e.g. advanced fossil energy system [2], small modular reactors [3], sustainable energy products [4], and ocean energy [5]. Of particular significance to this paper, which is concerned with tidal stream energy (TSE), is that, as pointed out in Ref. [5], TSE has reached TRL 7–8; i.e. full scale or prototype technology demonstration in an actual working environment system completed and qualified ready for deployment through test and demonstration. Furthermore, TSE is the most advanced of all ocean energy resources in terms of TRL, apart from tidal range energy, which despite achieving level 9 has been of limited deployment, although, there are a number of tidal lagoon proposals around the UK that may suggest a resurgence of the technology. In order to accelerate the transition of TSE from 7 to 8 to TRL 9, a full assessment is necessary of the diverse aspects, which impact the performance of a Tidal Energy Converter Array (TECA) which constitute the core of TSE deployment. It is towards this end that the work reported in this paper proposes to make a contribution, in furnishing an optimal TECA layout taking into account inter-turbine hydrodynamic and geometric interference, economic considerations, and environmental aspects.

The optimisation procedure of a TECA comprises various levels and aspects, such as technical, legal, financial and environmental. In the last decade, different mathematical optimisation strategies and models have been proposed, not only to maximise power generation, but also comprising aspects regarding the minimisation of capital and operational expenditures [6–17]. From these works, we can distinguish several approaches concerning TECA layout optimisation [8–17]. In Refs. [8–11] highly simplified tidal flow models were employed to estimate TEC array efficiency, which are attractive for their simplicity, but cannot capture the complex non-linear fluid flow interactions between turbines. The approach of [12–14] is more realistic. It consists in manually selecting TECA configurations from computationally demanding simulations that achieve an optimality criteria, and as a result the whole design parameter

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space cannot be explored. Furthermore, when considering conditions of real environments with complex bathymetries, non-uniform flows and several design variables and constraints, optimum solutions are not evident and are difficult to obtain. In Funke et al. [15,16] a gradient–based optimisation method is developed to maximise a function of the solution of the 2-dimensional shallow water fluid flow partial differential equations and of the design parameters, which comprise the location of turbines. This method is very appealing because it is capable of optimising large arrays made of hundreds of Tidal Energy Converters (TECs) at a reasonable computational cost and permits maximise different quantities as power or profit. However, the approach has the drawback that the free positioning of converters within the domain depends on mesh discretisation and that the 2-dimensional approach provides low resolution of wake characteristics. Another aspect is that it is restricted to the horizontal plane, discarding the vertical dimension for varying rotor placement through the water column. In González-Gorbeña [17], a Surrogate-Based Optimisation (SBO) of Computational Fluid Dynamics (CFD) experiments is applied to the optimisation of uniform turbine array layouts, i.e. similar streamwise (longitudinal) and similar spanwise (transversal) distances between TECs, under steady state uniform and non-uniform flows, respectively. Once a validated surrogate model is built, the method proves to be very time efficient (i.e. minutes) in the evaluation of numerous (i.e. millions) tidal energy turbine array layouts in the search for optimality criteria. As the number of design variables increases, so does the number of computer simulations at a ratio of approximately 10 times, with a considerable increase in computational costs, which is a disadvantage when using high fidelity CFD models. The advantages of the latter two methods are that TECA modelling is coupled with the hydrodynamics of the surrounding flow and they allow the mathematical formulation of constraint optimisation problems as in Refs. [7,17].

Within the mathematical formulation of the TECA optimisation problem, the incorporation of environmental constraints is still in an incipient level, and there is not any relevant work published on this topic. In part, this is due to the lack of a sufficiently deep understanding of the implications that large-scale tidal farm deployment has on the environment. Even though there are several prototypes, of different scales, which have been tested for the past few years, available data collected from monitoring campaigns are limited for an adequate assessment of environmental impacts for the purpose of utilisation in constrained optimisation problems. Environmental effects of a TEC project vary along its lifecycle; i.e. installation, operation and decommissioning. The direct consequence of operating a TEC in a tidal stream is the alteration of the surrounding flow field, which can lead to various environmental effects. In regions with muddy or sandy bottoms, the modified hydrodynamic field may affect sediment dynamics [18,19] and, therefore, impacting benthic fauna habitats [20], as well as other water quality parameters [21]. Other environmental concerns during the TEC operation phase are related to animal collisions with turbine blades, underwater noise, vibrations and electromagnetic field emissions, amongst others. These aspects need to be properly addressed when designing a TEC array to ensure the viability of the project as a whole.

The main objective of this work is to go a step forward in the aforementioned optimisation procedure by enhancing the sophistication of the mathematical formulation of the TECA layout problem previously defined in Ref. [17]. The innovation respect to the work of [6] resides in combining inline and staggered array layouts in a single optimisation model, consider bi-directional flows, and in exploring the influence of vertical displacement in the overall optimality criterion. For this purpose, the SBO method has been implemented to optimise a TECA layout of a fixed number of horizontal axis turbines. Ultimately, an optimisation model is formulated for maximising profit from electric energy production, while minimising detrimental environmental impacts associated with abnormal flow velocities in specific regions.

2. Optimisation methodology

In this Section, an explanation is provided of how the SBO approach has been implemented for optimising TECA layouts. SBO techniques [22,23] are widely used in the aerospace, automotive and mining industries [24–26], and in general are highly attractive when the use of expensive numerical codes is involved. It consists in approximating a computationally expensive model by a considerably less computationally expensive model. The approximation model, known as "metamodel", "surrogate" or "emulator", is built from a data set which is obtained from the design variable space and sampled using the methodology of Design Of Experiments (DOE). The built surrogate model is assessed and validated, and then it can be used to search the complete design variable space efficiently, at a considerably less computational cost than the original model. For a review on the construction of surrogate models see Ref. [27]. The SBO process is illustrated through the flow chart of Fig. 1.

2.1. Problem formulation

To the authors' knowledge, in all reported research work on the TECA layout optimisation problem, only horizontal dimensions have been taken into consideration to define turbine positions within the array [7–17]; i.e. longitudinal and lateral spacings. In open-channel flow, it is common practice that the vertical distribution of longitudinal free stream velocity is described by a logarithmic or power-law behaviour, with higher and lower flow velocities near the top fluid free surface and at the channel bottom, respectively. Under specific environmental conditions, as with strong opposite winds or the confluence of a river stream with a

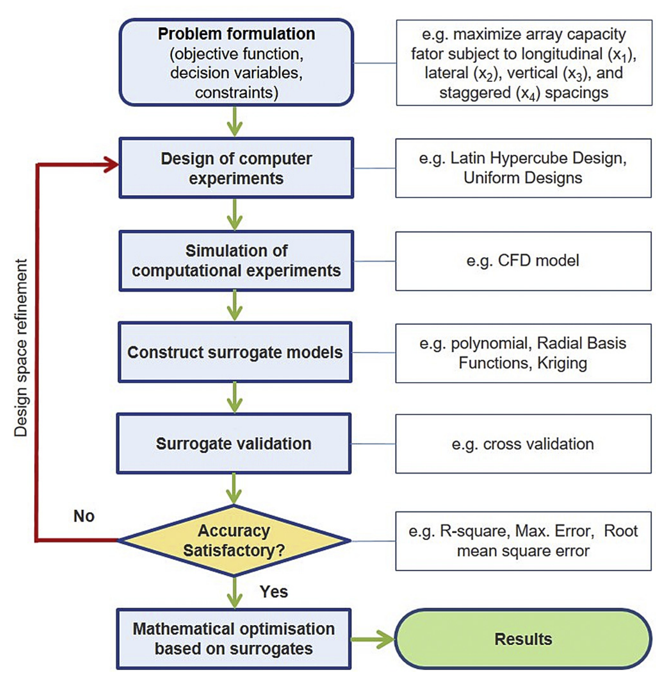

Fig. 1. Surrogate Based Optimisation process diagram.