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A semi-analytic method to optimize tidal farm layouts – Application to the Alderney Race (Raz Blanchard), France

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HIGHLIGHTS

- We present a new semi-analytic method designed to optimize the tidal farms' layout.
- The method is applied to the Alderney Race.
- The tidal directional spreading strongly affects the power and the optimal layout.

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ABSTRACT

The purpose of this paper is to present a semi-analytic model designed to optimize tidal farm layouts by maximizing the mechanical power production. A meta-heuristics method is used to find the turbine placement which minimizes the flow interaction between the turbines. The velocities in the wakes of turbines are simulated with an analytic model. The methodology is first applied to idealized cases: constant current magnitude and direction, and flow aligned with the turbines. Those preliminary tests permit to test the consistency of the results. In particular, they show that the optimal density of the devices grows with increasing turbulent intensities or increasing upstream velocity magnitude. The methodology is then applied to a site located in the Alderney Race (Raz Blanchard in French), situated between the Alderney Island and La Hague Cape (France). The results show that the optimal placement is influenced by the asymmetry of the tidal current and that the best layout is strongly dependent on the directional spreading of the current with respect to the predominant direction.

1. Introduction

Marine Renewable Energies (MREs) are recognized as a resource to be harnessed for the production of electric power because it is an alternative to fuel resources. The oceans represent two-thirds of the Earth and they constitute a huge energy resource [1,2]. There are four main types of MREs: thermal energy, chemical energy, biological energy and kinetic energy (waves and currents). Among them, tidal current energy seems to be the most attractive because it is highly predictable. The European objective is to produce 20% of the energy from renewable sources by 2020. Tidal energy provides an opportunity to increase the energy mix in France. France has the second production potential of electrical energy from MREs, behind the UK. French production potential is between 5 and 14 TW h/year. The Alderney Race (Raz Blanchard in French), situated between the Alderney Island and La Hague Cape (France), capitalizes about 50% of the national resource [3,4].

Maximizing the power extracted from a given tidal energy site requires finding the optimal density of devices and the most suitable type of layout (aligned, staggered or mixed configuration). In their synthesis and review paper, Vennell et al. [5] distinguish two main issues. The first issue, referred as macro-design of array, consists in determining the total number of turbines finding a compromise between the array power output and the power output of each machine. The second issue concerns the micro-design of arrays. It consists in determining the best array layout, the inter-row spacing and the number of devices per row taking into account the flow interactions between the turbines (the wake/duct effects). As observations in the real environment with tidal stream array are not available today, micro-design studies rely on either flume experiments with scaled turbines or numerical simulations. Using scaled experiments with velocity conditions representing the hydrodynamics of the Alderney Race [6,7], Myers and Bahaj [4] suggested an inter-row (longitudinal) spacing of 15 diameters

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and a lateral spacing of 3 diameters. Mycek et al. [8,9] also analyzed the wake effects between turbines placed in array using flume experiments. They highlighted the effect of the ambient turbulence on the wake characteristics and demonstrated that high turbulent intensities fasten the flow recovery and permit to reduce the longitudinal distance between two rows of machines. Flume experiments permits to understand the processes governing the flow interactions between turbines but only a limited numbers of idealized configurations can be tested and compared. Furthermore, those experiments have several limitations especially regarding the similitude of the Reynolds number. Computational Fluid Dynamics (CFD) is thus a complementary tool [10–14]. In CFD models of tidal farms, the turbines are represented with Blade Element Momentum (BEM) theory, Actuator Disk (AD) [15–20], Immersed Body Force Turbine [21] or frozen rotor method [22]. Because of their high CPU cost, only a limited number of turbine arrangements can be tested and compared. As only few array arrangements can be simulated, the turbine's placement cannot be optimized using an iterative procedure evaluating the performance of the array configuration at each iteration. The only exceptions are the studies of Funke et al. [23] and González-Gorbena et al. [24]. Funke et al. [23] succeed in optimizing the placement of turbines using a CFD model combining a bi-dimensional flow model with a gradient optimization algorithm. They demonstrated that the power production obtained with an aligned layout can be increased by 33% when using their optimization algorithm. González-Gorbena et al. [24] optimized uniform turbine array layouts subjected to different flow conditions using the Surrogate-Based Optimisation (SBO). Although the layout configuration is fixed (reducing the degree of freedom of the system), this method presents the main advantage of optimizing continuous and discrete design parameters simultaneously.

The CFD studies dedicated to the design of tidal farm (e.g. [18,21–23]) are commonly carried out considering stationary hydrodynamics conditions or regular layouts. This simplification permits to gain insight in understanding the flow interactions between turbines. However, it is not suited to analyze the effect of realistic tidal currents (large range of tidal current magnitude (spring/neap tide conditions), and flow arriving obliquely with respect to the predominant direction...) on the micro-design. Noteworthy, Nguyen et al. [25] analyzed the influence of the current incidence with respect to the mean flow direction on the production of a tidal farm containing 10 turbines. They examined two scenarios based on a hypothetical tidal farm located in the Alderney Race. For the first scenario, realistic tidal current data are used (the velocity constantly vary in magnitude and direction); for the second scenario, the incidence of the current with respect to the turbine axis has been "switched off" (i.e. the flow remains parallel to the longitudinal axis of the turbines). The results showed that the temporal variation of the current direction has a very limited effect on the overall production of the tidal farm but that it strongly influences the power production of each device, especially when several devices are aligned. Nowadays, only few studies use realistic tidal hydrodynamics as input of model dedicated to optimize the array arrangement. Additional investigations are therefore required to understand the influence of realistic hydrodynamic on the flow interactions between turbines and on tidal farm layout.

In the last few years, some authors investigated the possibility of using analytical models to assess the performances of tidal farm [26–28]. As far as we know, only Stansby and Stallard [29] used analytical methods to optimize the turbine arrangements of little tidal farms (two or three rows of devices). In their model, they used analytical equations validated with the experimental data of Stallard et al. [30]. This method successfully simulated the characteristics of the wakes measured experimentally. Studies of layout optimization are more advanced for wind turbines than for tidal turbines. They generally rely on the coupling between an optimization algorithm for finding the best turbine's positions and a simple model for representing the wakes and their interactions [31]. The most popular optimization algorithms in wind farm literature are Genetic Algorithm (GA) and Particle Smarm Optimization (PSO) algorithms [32–37]. The PSO algorithm is generally preferred to GA because it converges faster and gives better results as demonstrated by Pookpunt and Ongsakul [38].

In wind turbines applications, the wake of wind turbines is generally simulated with an analytical model deriving from the earlier works of Jensen [39]. Analytical wake models are suited for optimization problem because they permit testing a large number of configurations which is required when searching the best layout with an iterative procedure. With the perspective to adapt the wind turbine methodology to tidal turbine applications, Lo Brutto et al. [28] developed a wake model based on the theory of Jensen [39]. This wake model has been validated using a dataset obtained with a coupled CFD-Actuator Disk method. In the present paper, we integrate this wake model in an optimization algorithm in order to optimize the placement of tidal turbines.

The main objective of this paper is to present and validate a new optimization method for the tidal turbine positioning. The method is applied to several configurations with an increasing level of complexity permitting to give general guidelines as regards the placement of devices under different types of flows. In particular, we analyze the effects of the velocity magnitude, the turbulent intensity, the bi-directionality of the flow and the tidal current asymmetry. Finally, we apply the methodology using realistic tidal currents.

The Section 1 is dedicated to the description of the tidal farm layout optimization problem. The Section 2 presents the characteristics of the hydrodynamics in the Alderney Race. The results of the optimization method are detailed in Section 3.

2. Solving the layout optimization problem

We now present the layout optimization model starting with the parameters describing the tidal stream devices. When the incoming flow velocity U_0 is lower than the cut-in speed v_{ci}, the torque exerted by the fluid on the turbine blades is insufficient to move the blades and the mechanical power P is nil. When the incoming fluid speed U_0 exceeds the cut-in speed, the turbine starts to generate a mechanical power given by:

$$P = \frac{1}{2}\rho C_P \left(\frac{\pi D^2}{4}\right) U_0^3 \quad (1)$$

where ρ is the density of the fluid, C_p is the power coefficient and D is the turbine diameter. When the tidal speed exceeds the nominal speed v_r, the power is rated to the nominal power P_r [40,41].

Following the reference work of Jensen [39], the spatial distribution of the velocity in the wake of a turbine (2) can be obtained from a balance of momentum [42,43]:

$$\pi r_0^2 U_{w0} + \pi(\sigma^2 - r_0^2) U_0 = \pi \sigma^2 U_w \quad (2)$$

where U_w the velocity in the wake of the turbine at a downstream distance x (along the longitudinal axis), σ is the wake expansion which is assumed to be linear in x and U_{w0} is the minimum speed according to Betz limit:

$$U_{w0} = U_0\sqrt{1 - C_T} \quad (3)$$

In Lo Brutto et al. [28], the wind turbine model of Jensen was adapted to represent the flow in the wake of a marine turbine. Hydrodynamic data obtained from CFD simulations were used to develop the wake model [25,44]. The analysis of the CFD data indi-