Optimisation of Tidal Turbine Arrays

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Abstract
Commercial deployment of tidal stream turbines will likely involve large-scale arrays, in which energy extraction by a single turbine can impact the energy available to additional turbines. The overall energy capture of an array will be dependent on the turbine configuration. In this research a two-dimensional numerical model is utilised to develop an optimisation algorithm which determines an optimal array configuration for maximum energy capture with minimal environmental impacts. It is shown that optimal arrays will be staggered, producing higher efficiencies than symmetrical inline arrays as they consider the hydrodynamic interactions between individual turbines.

1. Introduction
Tidal stream energy has the potential to contribute significantly to global electricity demand, with worldwide tidal resource estimated at over 150 TW/h per annum [1]. The commercial viability of tidal turbine technology will largely depend on the expected energy capture and associated environmental impacts, which, in turn, will be dependent on the impacts of each individual turbine as well as any effects resulting from interactions between turbines. Numerical models have been used extensively throughout literature to simulate tidal energy extraction (e.g. [2]–[5]) and are a valuable tool in investigating optimum turbine array layouts (e.g.[6],[7]). The aim of this research is to develop a numerical methodology to determine an optimised array configuration that will produce maximum power output whilst minimizing adverse hydro-environmental impacts.

2. Methodology
2.1 Hydrodynamic Numerical Model
The numerical model used in this research is a modified version of DIVAST, a 2D finite difference, depth integrated, time-variant model, developed for shallow estuarine and coastal waters. The model consists of two main sections: a hydrodynamic model and a solute transport and water quality model. The hydrodynamic module is based on the depth integrated solution of the Navier-Stokes equations to determine values for the water surface elevations and horizontal depth integrated velocities. The model utilises an implicit finite difference scheme to solve the governing differential equations. Further details including descriptions and explanations of the governing equations and the modules solution scheme can be found in [8].

2.2 Development of the Optimisation Model
The power that is available for extraction by a turbine placed in tidal flows can be calculated as:

$$P_{ava} = \frac{1}{2} \rho A u^3$$

(1)

where $u$ is the total current velocity. The optimisation model was initially developed based solely on energy capture. Available power across the domain is determined for a no turbine scenario. Turbine 1 is deployed at the location of maximum power and the effects of energy extraction are incorporated into the model. This deployment leads to a change in current velocities across the domain, so the available power is recalculated, allowing a new location of maximum power to be determined, at which the 2nd turbine is placed. This is repeated until a user specified number of turbines has been added. Total energy captured by the array is determined as:

$$\sum P_{output} = \sum P_{ava} - \sum Remaining_A$$

(2)

where subscript $A$ denotes the turbine array.

The model is currently being developed to consider environmental impacts of turbine deployment. This is achieved by restricting deployment locations to sites at which the effects of energy extraction on current velocities will be less than 10% of the no turbine case. A check is incorporated into the model to ensure the turbine deployed does not impact significantly on energy capture. This check can be expressed as:

$$\Delta u = u_{NT} - u_T < 10\% u_{NT}$$

(3)

If this condition is met the number of turbines, $N$, is incremented by 1 and the addition process is repeated. If not, the turbine is removed and placed in the next location of maximum power.

3. Model Application
The energy extraction model was applied to an idealised rectangular channel domain, 4000m long and 1600m wide with a constant mean water depth of 50m and peak velocities of 2m/s. Tidal elevations were specified at the east and west boundaries. A repeating tide of 8m amplitude and 6.25hr period was specified at the western sea boundary, with a phase difference of 3.6 minutes between the two elevation boundaries. A horizontal model resolution of 20m was chosen to match the 20m turbine rotor diameter so flow around each individual turbine could be simulated.

4. Model Results
The model was simulated to deploy 12 turbines and a number of turbine scenarios were investigated. The two scenarios presented here are a) an inline array configuration and b) an optimised array with 1 rotor diameter spacing between adjacent turbines. Figure 4-1 shows the array configurations, the energy captured by
each turbine in the arrays and the impact on current velocities are presented in Figure 4-2 and Figure 4-3 respectively.

![Figure 4-1 (a) Inline and (b) Optimal turbine array configurations.](image)

![Figure 4-2 Energy captured (W/cycle) by each turbine in each array.](image)

![Figure 4-3 Relative percentage difference in peak ebb velocities (%).](image)

The low-performance of the inline array is also noted in the array efficiencies; with the optimised array achieving the maximum theoretical efficiency of 40% whilst the efficiency of the inline array was substantially lower at 32%. A greater impact on current velocities is found for the inline array compared to the optimised layout (Figure 4-3). For the inline configuration the cumulative effects of energy extraction by each downstream turbine causes the velocity deficit to increase through the array, with maximum deficit occurring at the end of each row. Turbines in the optimised array are positioned so that no turbines are placed in another’s ‘wake’, thereby allowing velocities to recover.

The results presented here are based solely on the power extraction model. Future work will involve comparing results when the significant impact on current velocities is incorporated. This is expected to further improve the efficiency of the optimised turbine, resulting in a greater energy capture.

3. Conclusions

An optimisation model has been developed to determine optimal configurations of tidal turbines for maximizing energy capture. The configuration, hydrodynamic impacts, power output and efficiency of an optimal 12 turbine array are compared with those for an inline array. The optimised layout is found to have a lesser impact on velocities and have a higher energy capture and array efficiency than the symmetrical inline array. The optimisation model is currently being further developed to incorporate minimising environmental impacts.

References


