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Investigation of the performance of a staggered configuration of tidal turbines using CFD

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ABSTRACT

This paper investigates the influence of wake interaction and blockage on the performance of individual turbines in a staggered configuration in a tidal stream farm using the CFD based Immersed Body Force turbine modelling method. The inflow condition to each turbine is unknown in advance making it difficult to apply the correct loading to individual devices. In such cases, it is necessary to establish an appropriate range of operating points by varying the loading or body forces in order to understand the influence of wake interaction and blockage on the performance of the individual devices. The performance of the downstream turbines was heavily affected by the wake interaction from the upstream turbines, though there were accelerated regions within the farm which could be potentially used to increase the overall power extraction from the farm. Laterally closely packed turbines can improve the performance of those turbines due to the blockage effect, but this could also affect the performance of downstream turbines. Thus balancing both the effect of blockage and wake interaction continues to be a huge challenge for optimising the performance of devices in a tidal stream farm.
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1. Introduction

The study of turbine to turbine interaction is crucial to understand how energy shadowing of an array of devices influences energy extraction by the individual devices. Simple turbine to turbine interactions can be investigated using small scale experiments on two or three turbines, but the feasibility of experimental studies with multiple devices in a tidal stream farm is challenging due to the practical and cost implications of an experiment involving tens of devices within a sufficiently large flow domain. Consequently, researchers are focusing on exploring alternative methods to investigate the flow features around tidal turbines. Computational Fluid Dynamics (CFD) studies currently represent an interesting alternative for these kind of studies.

The study of wake interactions of wind turbines using both analytical and CFD techniques is well documented as this technology has been in the forefront for many years [1–6]. Recently there have been several efforts to apply similar techniques to investigate the wake interactions of turbines in tidal stream farms, taking into account the fundamental differences in the working environments between the two technologies. As in the experimental approach, there are computational cost aspects which come into play when CFD techniques are used to study the flow features of groups of turbines. For single turbine simulations either in wind or tidal turbines, it is possible to employ detailed modelling techniques such as tracking the individual blade motions with current computational resources. As the number of devices increases, such as in the study of arrays of devices, the computational cost spirals and detailed blade modelling becomes impractical. In such cases we must investigate lower cost turbine modelling such as actuator disk methods.

Study by Ref. [7] used a blade element and actuator disc method to investigate the wake interaction of a tidal stream farm with 5 rows of turbines configured in the stream-wise direction. This study showed that the power coefficient of the second row was lower than the rest of the devices due to huge wake interaction from the first row, but the turbines from the third row onwards showed better power coefficients due to high wake recovery within the array. Those comparisons have been made based on a single resistance coefficient. Study of a staggered configuration of arrays of devices by Refs. [8,9] showed an acceleration of the bypass flows due to the venturi created by the turbines which is important to improve the performance of any downstream devices. A similar study by Ref. [10] observed that a staggered configurations of

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turbines with a small longitudinal spacing offers high efficiency. Experimental studies of arrays of devices by Refs. [11,12] also showed that with a particular inter-turbine spacing there is the potential of accelerated flow regions which can be used for high power production by deploying turbines in those regions [12]. particularly indicated a flow acceleration of up to 14% can be achieved due to the presence of arrays of devices. The experimental work also reveals there is less wake propagation downstream of single row of turbines if the lateral spacing is increased, otherwise laterally closely spaced turbines would produce a huge plug flow of slow water which could affect the performance of downstream devices. They have suggested that an off-set or staggered configuration would provide a better option and allow longitudinally closely packed devices to be deployed with less wake interaction and possibly higher power extraction due to accelerated bypass flows. These studies indicated the importance of analysing the influence of turbine to turbine interactions of arrays of devices in order to optimize the power extraction.

Calibration of the energy extraction in a tidal stream farm inevitably depends upon the inflow conditions to each devices. Given that the turbines interact with each other these inlet conditions are themselves unknown at the start of the calculation, which makes it difficult to apply the correct resistance coefficient to each of the downstream row of turbines. The aim of this study is therefore to obtain a range of operating points for turbines in a staggered configuration tidal stream farm. The turbine analysed is the cross flow Momentum-Reversal-Lift tidal turbine [13], a novel design intended for use in shallow estuaries in large farm installations (100 + turbines). Relative comparisons of the power extraction by a base case tidal turbine and turbines in a tidal farm was also carried out to understand the influence of wake interactions on the performance of individual devices.

2. Methodology

Several comparisons of LES and RANS modelling techniques have been reported due to their increased importance in modelling turbulent flows. It is generally agreed that RANS is the simpler technique but it lacks accuracy especially in applications where there are more complex flows such as vortex shedding, large separation zones, and high streamline curvature [14–17]. In particular, RANS relies on an implicit assumption that there is a scale separation between all turbulent components of the flow, which will be replaced by a statistical model, and any deterministic transient motions such as vortex shedding, pulsatile pumping or (as here) flow components associated with the blade motions. In cases such as this one where there is a significant overlap between the deterministic and large turbulent scales, LES is known to be the preferred approach. Despite this, an initial set of simulations was conducted for the new MRL device in order to compare the two modelling techniques for this turbine. The analysis indicated that the LES modelling technique showed better results for the MRL device. The detailed discussions and comparisons of the two models are reported in Ref. [13]. Thus the LES modelling technique has been implemented for this research work.

2.1. Large eddy simulation

The Large Eddy Simulation (LES) modelling approach resolves the large-scale turbulent motions by filtering the Navier-Stokes equations, and the small-scale motions are modelled using Sub-Grid Scale (SGS) models [18–20]. It is generally accepted that the small scale motions in turbulent flow, whilst most numerous, are similar from place to place in the flow and across different flow types, and thus can accurately be replaced by a statistical model. The resolved (Grid Scale) motions, either deterministic or turbulent, are case specific and thus have to be explicitly resolved [21]. The body force (F_b, see details in 2.2) applied by a turbine against the flow is implemented as source term in the LES equation of momentum conservation (1), and solved together with a mass continuity Equation (2). The source terms are only applied in cells within the turbine blade regions. The LES governing equations are a combination of filtered Navier-Stokes equations and the source terms written as:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i\overline{u}_j\right) = -\frac{1}{\rho}\left(\frac{\partial \overline{p}}{\partial x_i} + \delta_{i1}\frac{\partial \langle P\rangle}{\partial x_1}\right) + 2\nu\frac{\partial}{\partial x_j}\overline{S}_{ij} - \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + \overline{F}_s + \overline{F}_b \tag{1}$$

The continuity equation is given as:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{2}$$

Where the bar $\overline{(\cdot)}$ defines the resolved scales; $\overline{u}$ is the filtered velocity, $\overline{p}$ is the filtered pressure; ν is a kinematic viscosity; δ_{i1} is the Kronecker-delta and $\frac{\partial\langle P\rangle}{\partial x_1}$ is the driving force, a constant streamwise pressure gradient, τ_{ij} is the SGS Reynolds stress. $\overline{S}_{ij}$ is the strain rate of the large scales or resolved scales and is defined as:

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_i}{\partial x_i}\right) \tag{3}$$

The resulting SGS stresses from the filtering processes are unknown and need modelling. These stresses represent large scale momentum fluxes resulting from the unresolved scales. Most of the time, these stresses have been approximated by SGS models based on the eddy viscosity concept. The most commonly employed hypothesis in the SGS turbulence models is the Boussinesq hypothesis [22] which calculates the SGS stress as a linear function of the rate of strain tensor. Popular SGS models include the Smagorinsky model, the one equation eddy viscosity, and dynamic variants of these, in which the model coefficients can be evaluated mathematically using grid scale information. A study by Ref. [23] showed that the one-equation eddy viscosity model is much better than the Smagorinsky model because of its weak dependence on the filter width and Reynolds number and therefore is suited for applications in coarse grid LES. Thus, this SGS model was implemented in this study.

The one-equation eddy viscosity model developed by Ref. [24] has been used in a wide range of turbulent problems. Based on [24], the Sub-Grid stresses are defined as:

$$\tau_{ij} = \frac{2}{3}k_{sgs}\delta_{ij} - 2\nu_t\overline{S}_{ij} \tag{4}$$

where ν_t is the SGS eddy viscosity given as:

$$\nu_t = C_k\overline{\Delta}\sqrt{k_{sgs}} \tag{5}$$

and the SGS kinetic energy, k_{sgs}, is given as:

$$k_{sgs} = \frac{1}{2}\left(\overline{u_i u_i} - \overline{u}_i\overline{u}_i\right) \tag{6}$$

The transport equation for the SGS kinetic energy is defined as [23]:

$$\frac{\partial k_{sgs}}{\partial t} + \overline{u}_i\frac{\partial k_{sgs}}{\partial x_i} = -\tau_{ij}\frac{\partial \overline{u}_i}{\partial x_j} - C_c\frac{k_{sgs}^{3/2}}{\overline{\Delta}} + \frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k_{sgs}}{\partial x_i}\right) \tag{7}$$

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