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Numerical investigations of the effects of different arrays on power extractions of horizontal axis tidal current turbines

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ABSTRACT

As the tidal current industry grows, power extraction from tidal sites has received widespread attention. In this paper, a blade element actuator disk model that is coupled with the blade element method and a three-dimensional Navier–Stokes code is developed to analyse the relationship between power extraction and the layout of turbine arrays. First, a numerical model is constructed to simulate an isolated turbine and the model is validated using experimental data. Then, using this validated model, the power extraction of horizontal axis tidal current turbines using different tidal turbine arrays and rotation directions is predicted. The results of this study demonstrate that staggered grid array turbines can absorb more power from tidal flows than can rectilinear grid array turbines and that staggered grid array turbines are less affected by the rotation of upstream turbines. In addition, for staggered gird arrays, the relationships between power coefficients, lateral distance and longitudinal distance are discussed. The appropriate lateral distance is approximately 2.5 turbine diameters, whereas for the longitudinal distance, the largest value possible should be used. The relative power coefficient can achieve 3.74 when the longitudinal distance is 6 times the turbine diameter. To further increase the power extraction, this study suggests an improved staggered grid array layout. The relative power coefficient of the improved four-row turbine arrays is approximately 3–4% higher than that of the original arrays and will increase as the distance between the second-row and third-row increases. Considering only the first two rows of turbines, the total power extraction can be 11% higher than for an equivalent number of isolated turbines.

1. Introduction

Extracting energy using tidal currents induced by the gravitational force exerted by the Moon is regarded as one of the most promising alternative energy resources because of its minimal environmental footprint and high energy density. The conversion of tidal current energy to useful energy involves two processes. The primary process is extracting kinetic energy from tidal currents and converting the energy to mechanical energy at the rotor axis, and the secondary process is the conversion of the mechanical energy into useful energy. The current work focuses on the primary process. In this process, the device used to harness the tidal current energy is the tidal current turbine. Consequently, interest in investigating tidal current energy turbines has increased in recent years. Tidal current turbines can be classified as either horizontal or vertical axis turbines. To improve the efficiency of tidal current power extraction, many experimental and analytical investigations have been conducted [1–3]. Several pre-commercial prototypes have been installed in the sea by vendors such as Seagen, Underwater Windmills and Verdant Power. Compared to the design of tidal turbines, the study of tidal turbine layout has more practical significance.

Unlike wind farms, tidal current sites are always built in rivers, channels and offshore areas. The configuration of a site is limited by water depth and channel width, among other factors. Thus, the layout of tidal current turbines significantly affects the power output of a tidal current site. Investigation of the interaction between multiple tidal turbines is required. Harrison et al. [4] predicted the performance of stand-alone turbines and investigated the wake velocity recovery within an array that contains five turbines in a line. Turnock et al. [5] modelled tidal current turbine wakes using a coupled RANS-BEMT approach and predicted the energy capture for an array of HATTs assuming that the power output from each line is reduced by the same factor. A few investigations of twin-turbine systems with horizontal or vertical axis turbines have been performed [6,7]. The wake and turbine

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Nomenclature

A	disk area (m^2)
a	axial flow induction factor
a'	tangential flow induction factor
C_L	lift coefficient
C_D	drag coefficient
C_P	power coefficient
C_T	thrust coefficient
$\tilde{C}_P$	relative power coefficient
$\tilde{C}_T$	relative thrust coefficient
d	diameter of the actuator disc (m)
R	blade tip radius (m)
r	is radius of the annular element (m)
U_0	free stream velocity (m/s)
W	resultant velocity on the rotating blade (m/s)
Ω	is rotor angular velocity (rad/s)
TSR	tip speed ratio $= \Omega R/U_0$
CFD	computational fluid dynamics

characteristics of a counter-rotating double-row set of three-bladed tidal turbines were characterised by Doherty et al. [8]. The results demonstrate that there is a negligible increase in the power generated, but there is an increase in the axial load on the turbine, and the initial wake recovery of the contra-rotating turbine is faster than that of a single turbine. There have been some studies of the arrangement of tidal current turbines [9]. However, counter-rotation of the turbines was not considered, and the lateral spacing of turbines was fixed. A recent study analysed the flow field around a two-row array, the device–device interaction and the structure of the far wake region [10]. The results identified an optimal lateral distance between devices where, under certain conditions, the flow can be accelerated between a pair of rotor disks. This accelerated region of flow possessed 22% more kinetic energy than the flow far upstream, and there was no measurable negative effect on the two actuator disks. To the best of our knowledge, no one has used a blade element actuator disk approach to investigate the power extraction of different arrays of horizontal axis tidal current turbines. We therefore decided to conduct a detailed study of the power output from different tidal turbine arrays. Preliminary studies have discussed the limits of power capture in channels and examined the interaction between multiple devices placed across a channel [11,12]. The results demonstrated that the Lanchester-Betz limit ($C_P = 16/27$) for the maximum efficiency of a turbine in an infinite domain is increased by a factor of $(1-A/A_c)^{-2}$ in a channel, where A is the device area and A_c is the channel cross-sectional area. This factor is equivalent to the blockage correction that should be applied to tidal energy turbines tested in a finite-width channel. The aim of our work is to determine the performance characteristics of horizontal axis tidal current turbines interacting with others in different arrays. Thus, we assume that the tidal turbine array is operated in an infinite domain.

2. Numerical method and validation

2.1. Numerical method

The actuator disk model has long been used to study propeller and wind turbine aerodynamics [13], and this concept has recently been introduced to model tidal current turbines. The combination of a three-dimensional Navier–Stokes code and a blade element momentum (BEM) model was applied in the actuator disk model by Harrison [14], Jourieh [15], and Turnock [5]. The actuator disk model assumes that the rotor geometry can be modelled as a thin cylinder and that the actuator disk has radius equal to the wind turbine radius R and axial thickness e. In this paper, the influence of the actuator disk thickness is not discussed; instead, it is assumed to equal 0.1–0.2 of the blade chord length, as suggested by other studies. To achieve the same effect as rotating blades, momentum sources are added to the CFD solver; these sources are only applied at elements within the disk domain. The equations of momentum and mass conservation are shown in Eqs. (1) and (2).

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial(\rho U_i U_j)}{\partial x_j} = -\frac{\partial(P)}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial(U_i)}{\partial x_j} + \frac{\partial(U_j)}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) + \rho g_i + S_i \tag{1}$$

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{2}$$

Above, ρ is the density of water, $U_i(i = u,v,w)$ are the velocity components of the water averaged over time, $x_i(i = 1,2,3)$ is the distance to the element, P is the mean pressure, μ is the coefficient of viscosity, u' is an instantaneous velocity fluctuation relative to the mean velocity, $-\rho\overline{u_i' u_j'}$ is the Reynolds stress, $g_i(i = x,y,z)$ is the gravitational acceleration, and $S_i(i = x,y,z)$ is the source of momentum.

Here the source terms are obtained using the BEM theory, which is often used to predict the hydrodynamic performance of tidal current turbines. In this paper, however, the BEM theory must be modified before it is coupled to the Navier–Stokes code. The term $U_0(1-a)$ is replaced by U_u, which can be obtained from the flow field computed by the CFD code. Thus, the resultant velocity W is expressed as

$$W = \sqrt{U_u^2 + [\Omega r(1 + a')]^2} \tag{3}$$

The coefficient of rotational induced velocity is deduced in this paper, the expression is

$$a' = \sqrt{U_v^2 + U_w^2 - \frac{(U_v x_2 + U_w x_3)^2}{x_2^2 + x_3^2}}\Big/\Omega r \tag{4}$$

Considering the swirl effect of wake, the interference between upstream and downstream turbines and the influence of the different relative positions of tidal current turbines, the positive and negative of a' need to be determined using $\vec{r} \times \vec{u}_\tau$. As shown in Fig. 1, assuming the turbine rotation is clockwise, a' is positive when $\vec{r} \times \vec{u}_\tau > 0$, and negative otherwise.

The lift and drag coefficients C_L and C_D are usually obtained from hydraulic experiments performed on the blade section airfoil. However, very few experimental data are available. To validate the model used in this paper, NACA63-8xx sections are selected and the lift and drag coefficients are obtained from the flow field computed by the CFD code. The numerical results are in good agreement with the limited experimental test results of Molland [16].

The actuator disk is divided into n annular elements along the radial direction. Assuming the radial thickness of each annulus is dr, the volume of an elementary annulus of radius r is $dv = 2\pi redr$. The blade forces are distributed over the actuator disk by defining the volume cells in a Cartesian coordinate system. The source terms at an arbitrary point of the volume are expressed as