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Modelling tidal current energy extraction in large area using a three-dimensional estuary model

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ABSTRACT

This paper presents a three-dimensional modelling study for simulating tidal current energy extraction in large areas, with a momentum sink term being added into the momentum equations. Due to the limits of computational capacity, the grid size of the numerical model is generally much larger than the turbine rotor diameter. Two models, i.e. a local grid refinement model and a coarse grid model, are employed and an idealized estuary is set up. The local grid refinement model is constructed to simulate the power generation of an isolated turbine and its impacts on hydrodynamics. The model is then used to determine the deployment of turbine farm and quantify a combined thrust coefficient for multiple turbines located in a grid element of coarse grid model. The model results indicate that the performance of power extraction is affected by array deployment, with more power generation from outer rows than inner rows due to velocity deficit influence of upstream turbines. Model results also demonstrate that the large-scale turbine farm has significant effects on the hydrodynamics. The tidal currents are attenuated within the turbine swept area, and both upstream and downstream of the array. While the currents are accelerated above and below turbines, which is contributed to speeding up the wake mixing process behind the arrays. The water levels are heightened in both low and high water levels as the turbine array spanning the full width of estuary. The magnitude of water level change is found to increase with the array expansion, especially at the low water level.

1. Introduction

In response to the growing needs for the development of renewable energies, tidal current energy has received widespread attention in both the commercial and academic fields because of the high predictability of tides, the low environmental impact without large scale constructions, and the relatively low investment needed for tidal turbines (Grabbe et al., 2009; Kim et al., 2012).

An assessment of the tidal current energy resources is the first step to predict the level of energy production that can be achieved and to select locations with the greatest potential. Two assessment approaches are used, including direct measurement (Fairley et al., 2013; Myers and Bahaj, 2012) and numerical modeling. Most researchers have used the numerical modelling approach to investigate tidal current energy resources.

Garrett and Cummins (2005) applied a one-dimensional model to evaluate the maximum tidal power potential of a tidal channel. In this model, the water bodies at the two ends of the channel were considered to be of sufficient size such that the tidal elevations were unaltered by energy extraction. Assuming the turbines were deployed over the full width of the channel cross-section, the maximum power available for such a tidal channel was proportional to the amplitude of tidal difference and the maximum volume flux. The main drawback of this approach was the requirement of a head difference over the channel which may be difficult to measure. Vennell (2011) recognized this inadequacy and adapted the results using an approximate analytic solution to calculate the tidal current potential (Sutherland et al., 2007).

The above one-dimensional models have been applied to assess the maximum available power from the Bay of Fundy (Karsten et al., 2008), Johnstone Strait (Sutherland et al., 2007), and Masset Sound (Blanchfield et al., 2008). However, for navigational requirements and the safe passage of marine mammals, the deployment of tidal turbine arrays is not expected to cover the full vertical or horizontal extent of a channel. Garrett and Cummins (2008) analyzed the special case of a channel that isolated turbines or partial fences were employed, the results indicated that the available power dropped below that obtained from a complete fence.

A flow flux based approach has also been proposed to assess the preliminary resource of the available tidal power. Carballo et al. (2009) adopted this approach to evaluate the tidal current energy in the Ria de Muros. Chen et al. (2013) and Bomminayuni et al. (2012) used this method to predict the tidal current resources around Kinmen Island of Taiwan and Rose Dhu Island

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of Georgia, respectively. However, this approach includes an empirical coefficient of energy extraction rate, which is difficult to determine. Bryden and Melville (2004) suggested that the value of this coefficient was dependent on both the tidal flow and turbines layout.

Three approaches have been used to simulate the tidal hydrokinetic energy extraction by tidal turbines. The first is a bottom friction approach, in which the tidal energy dissipation associated with the presence of tidal turbines is approximated by adding a bottom friction term. This approach is commonly used in analytical models and depth-averaged two-dimensional numerical models (Neill et al., 2012). The second is a momentum sink approach, in which the loss of momentum due to tidal energy extraction is added to the momentum equations (Yang et al., 2013; Defne et al., 2011). The third is the blade element actuator disk approach, which couples a blade element model with a three-dimensional Navier–Stokes model to analyze the performance of turbines interacting with others. This approach is generally used for the model turbines deployed in an area within 10 m^2 (Bai et al., 2013).

There have been some studies of tidal current energy evaluation for large areas with turbines effects being considered (Vennell, 2012a, 2012b). For three-dimensional numerical model, the grid spacing is much larger than the diameter of turbines due to the limits of computational capacity, the effect of isolated turbines could not be precisely simulated. Grid refinement is a valid approach to realize the more precise simulation, but it is only suitable for local small areas, not for the large area over hundreds of square kilometers. Among the existing studies, the tidal farm is often simplified into a combined thrust and included in a grid element. However, the thrust is usually represented as an algebraic sum of the isolated turbine thrust, although it is unclear whether the two are really equivalent. This paper presents a study of power extraction from large-scale turbine arrays combining two three-dimensional potential numerical models. First, a local grid refinement model is constructed to simulate the power production of isolated turbines and to analyze its influence on the flow field, which is the basis for turbine array deployment. Second, numerical experiments are carried out to qualify a combined thrust coefficient for the multiple turbines located in a grid element of coarse grid model. Third, large-scale arrays, with single row and multi-row turbines, are deployed in an idealised estuary to investigate the tidal stream energy extraction potential and its effects on hydrodynamic process.

2. Methodology

2.1. Numerical model

A three-dimensional hydrodynamic model, Delft3d-Flow, is modified in this study to predict the power generation from turbines, with the momentum sink terms being added to the momentum equations. In order to better follow the topography and water surface, the orthogonal curvilinear co-ordinate is adopted in horizontal direction, and the sigma co-ordinate is used in vertical direction. Based on the shallow water and Boussinesq assumptions, the model solves Navier–Stokes equations for an incompressible fluid by taking account of the effects of earth's rotation, barotropic pressure gradients and the $k-\varepsilon$ turbulence closure model. In this 3D model, the vertical velocity is computed from the continuity equation.

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)u\sqrt{G_{\eta\eta}}]}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)v\sqrt{G_{\xi\xi}}]}{\partial\eta}=Q \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial\eta}+\frac{\omega}{d+\zeta}\frac{\partial u}{\partial\sigma}-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}+\frac{vu}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}-fv=-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi+F_\xi+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_v\frac{\partial u}{\partial\sigma}\right)+M_\xi \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial\xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial\eta}+\frac{\omega}{d+\zeta}\frac{\partial v}{\partial\sigma}+\frac{vu}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial\xi}-\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial\eta}+fu=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_v\frac{\partial v}{\partial\sigma}\right)+M_\eta \tag{3}$$

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)u\sqrt{G_{\eta\eta}}]}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)v\sqrt{G_{\xi\xi}}]}{\partial\eta}+\frac{\partial\omega}{\partial\sigma}=H(q_{in}-q_{out}) \tag{4}$$

where ζ=free surface elevation above the reference plane; d=depth below the reference plane; f=Coriolis parameter; ω=fluid velocity in the z direction; ρ_o=reference density of water; P_ξ, P_η=gradients of hydrostatic pressure in the ζ and η directions, respectively; F_ξ, F_η=turbulent momentum flux in the ζ and η directions, respectively; and M_ξ, M_η=sink of momentum in the ζ and η directions, respectively.

For the spatial discretization the model employs the Arakawa-C approach and staggered grid, in which the water level is computed at grid cell center, whereas the flow velocity is defined at the midpoint of the grid cell faces. The discretization of the horizontal advection terms in the momentum equations is carried out by means of the Cyclic method (Stelling and Lendertse, 1991). For the temporal discretization the model adopts a semi-implicit ADI algorithm.

2.2. Turbine representation

The horizontal-axis tidal turbine is placed into the flow and it covers several vertical layers, the thickness of the turbine blade is considered very small. Across the rotor part momentum is exchanged, and some is lost from the flow due to power generation. In the model, the effects of turbine are represented by the momentum sink term M.

In the ξ direction, the total momentum sink rate by a tidal turbine unit can be defined in the general form

$$M_\xi=-\frac{1}{2}(C_T+C_D)u\sqrt{u^2+v^2} \tag{5}$$

where C_T, C_D=thrust coefficient and drag coefficient, respectively. In the η direction, similar equations can be derived. C_T depends on the number of blades and their geometries, and it is also related to the flow speed. The drag force, induced by the physical structure of turbine blades and supporting poles, is not discussed in this study.

The model assumes that turbines are free to rotate such that the plane of their swept area is always aligned perpendicular to the direction of flow for maximum power generation. The tidal current energy extracted by a tidal turbine can be calculated using the following equation:

$$P=\frac{1}{2}C_p\rho A_t|u|^3 \tag{6}$$

where A_t=swept area of the turbine and C_p=dimensionless power coefficient which describes the efficiency of turbines. Studies for horizontal axis turbines show that there is a non-linear relationship between C_p and C_T (Bahaj et al., 2007; Yang and Lawn, 2011).