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Effects of stream turbine array configuration on tidal current energy extraction near an island

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ABSTRACT

Enhanced tidal currents around islands appear to present the potential for power extraction. In this research, a three-dimensional numerical model is applied to investigate the naturally occurring tidal dynamics and the extractable energy from turbines close to Zhaitang Island, located off the east coast of China. In the model, the effect of tidal turbine is represented by a horizontal thrust and added to the momentum equations. To determine a better configuration of turbine array, a detailed work has been undertaken to investigate the combined influences of the topographic features and array arrangement on the performance of power generation. First, three single row arrays are examined with lateral spacing being 2, 3 and 4 times rotor diameters. Then, corresponding to each lateral spacing, three multi-row arrays in a staggered manner with longitudinal spacing being 5, 10 and 15 times rotor diameters are developed. It has been found that single row arrays with higher local blockage outperform arrays with lower blockage. While for multi-row arrays, the performance of inside turbine is significantly experienced the wake influence of upstream turbines, which can be weakened with an increment of turbine spacing. And a remarkable improvement of turbine performance is observed as the longitudinal spacing increases to 10 times rotor diameters. However, the change pattern of power extraction is mainly dependent on that of naturally kinetic energy when the turbine density is further decreasing in the given region.

1. Introduction

High tidal currents commonly occur in narrow straits and estuaries, or around headlands (Charles and Roger, 2009). These locations, where the tidal currents are enhanced because of the geometric effect, are generally desired sites for the deployment of tidal current turbines (Rourke et al., 2010). In contrast to tidal channels, islands and coastal headlands have an important feature that the tidal streams are unbounded on the ocean side. Many promising sites for tidal energy extraction can be found near headlands and islands, e.g., Anglesey and Portland Bill in UK, and Zhoushan and Zhaitang Islands in China.

Zhaitang Island is a small island located off the east coast of the Yellow Sea, China (Fig. 1). The spring tidal currents can reach over 1.5 m/s in the south-eastern area of Zhaitang Island, which has been considered to be one of the candidate sites for testing and development of tidal stream energy in China (Li et al., 2010; Wang and Lu, 2009). A testing research has been conducted with two horizontal axis turbines in 10 m diameter, and the next stage of progression is expected to involve the installation of multiple devices.

The deployment of an array of tidal stream turbines in a laterally unbounded flow is complicated by the fact that the extraction of energy and obstruction caused by the array may lead to flow diversion around the array, altering the natural distribution of tidal currents and ultimately limiting the power potential (Draper et al., 2013). Various approaches have been taken to investigate the influence of tidal devices on the accurate predictions of the energy potential close to headlands. Blunden and Bahaj (2006) conducted a numerical modelling study to assess the tidal resource close to the Portland Bill headland, with a turbine array being represented by an additional bed roughness term in the governing flow equations. Neill et al. (2012) also employed this approach to simulate the tidal energy extraction near a coastal headland. Draper et al. (2013) and Adcock (2014) analysed the energy distribution off an idealised headland, and the effects of turbine arrays were represented by line sinks of momentum related to the Linear Momentum Actuator Disk Theory (Houlsby et al., 2008; Draper, 2011). This method was also applied to evaluate the tidal energy resource of the Pentland Firth and Anglesey Skerries in UK by

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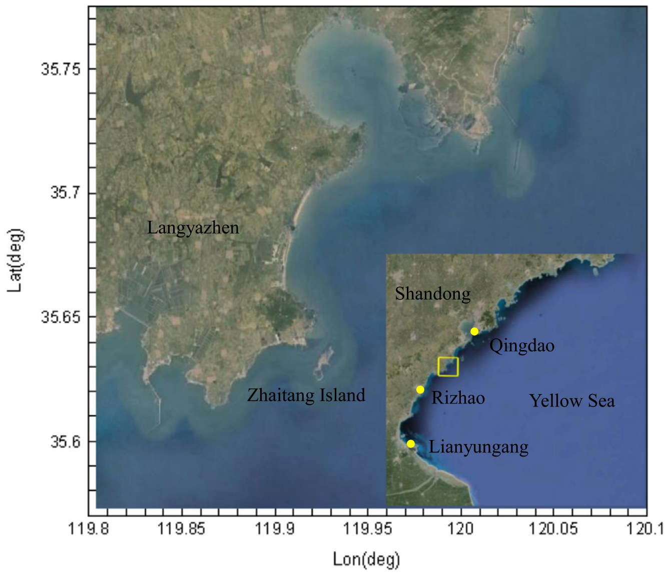

Fig. 1. Location map of Zhaitang Island off the east coast of Yellow Sea, China.

Adcock et al. (2013) and Serhadlioglu et al. (2013), respectively. Hashemi et al. (2015) employed the TELEMAC-2D hydrodynamic model to investigate the effects of wind waves on the tidal energy extraction from a tidal stream array installed off the northwest headland of Anglesey, UK.

Although these studies provide useful insights into the effects of tidal devices deployed close to a headland, it is not enough to understand the characteristics of energy extraction in the vicinity of Zhaitang Island. In the present study, a three-dimensional numerical model is used to investigate the potential influence of deploying a tidal stream turbine array off the Zhaitang Island. A momentum sink term is introduced to the momentum equations to represent the effects of tidal turbines. Firstly, the topographic features and tidal physics are analysed to determine an appropriate region for energy extraction. Secondly, numerical experiments are conducted to examine the performance of turbine array arrangements, including different configurations and turbine density. Finally, the disturbance of a better turbine array to the flow field is analysed.

2. Methodology

2.1. Turbine representation

Two horizontal-axis tidal turbines with three blades, shown in Fig. 2a, has been deployed at the southeast of Zhaitang Island. Based on the testing research, horizontal-axis turbine is employed in the numerical model. The presence of turbines for energy extraction results in a reduction in the momentum of the flow passing through the area swept by the turbine blades (Stallard et al., 2013). Moreover, the flow passing through the turbine rotor experiences a discontinuity in static pressure along the rotor-centre line (Roc et al., 2013). According to the Blade Element-Momentum Theory (Burton et al., 2011), the mass flow rate is the same everywhere along the stream-tube, as shown in Fig. 2b. And the pressure drop induced by the presence of a turbine can be expressed as follows:

$$(p_t^+ - p_t^-) = (U_\infty - U_w)\rho U_\infty (1 - a) \quad (1)$$

where, $a=$ induction factor, $a = \frac{U_\infty - U_t}{U_\infty}$; $p_t^{+,-}=$ pressure before and behind turbine rotor; $U_w=$ wake velocity, $U_w = (1-2a)U_\infty$; $\rho=$ seawater density; $U_\infty=$ velocity far upstream of the turbine; $U_t=$ velocity on swept area, A_t. According to Eq.(1) and the wake velocity, the force on the swept area can be written as follows:

$$F = (p_t^+ - p_t^-)A_t = 2\rho A_t U_\infty^2 a(1-a) \quad (2)$$

Before representing the effect of turbine on tidal flow, additional assumptions are made. Firstly, the effects of the supporting structures on the flow are neglected, and the blade thickness is considered very small. Secondly, turbine rotor plane is assumed always normal to the incoming flow for the maximum power extraction. Thus, the flow thrust force inserted on the turbine rotor for energy extraction can be expressed as follows:

$$T = F = \frac{1}{2} C_t \rho A_t U_\infty^2 \quad (3)$$

where, $C_t=$coefficient of thrust, with the value being 0.8 in the model. From Eqs.(2) and (3), the induction factor can be rewritten as: $a = \frac{1}{2}(1 - \sqrt{1 - C_t})$. However, the real flow field is likely to be disturbed by the presence of a turbine. Therefore, T should be a function of the flow velocity on the swept area. From the induction factor and Eq.(3), the thrust force can be rewritten as follows:

$$T = \frac{1}{2}\left(4 \times \frac{1 - \sqrt{1 - C_t}}{1 + \sqrt{1 - C_t}}\right)\rho A_t U_t^2 \quad (4)$$

2.2. Extractable power

The energy extracted by a tidal turbine is converted into useable power from the torque applied on the rotor, and the extractable power is equivalent to the rate of work done by the turbine thrust. The expression is given as follows:

a

b

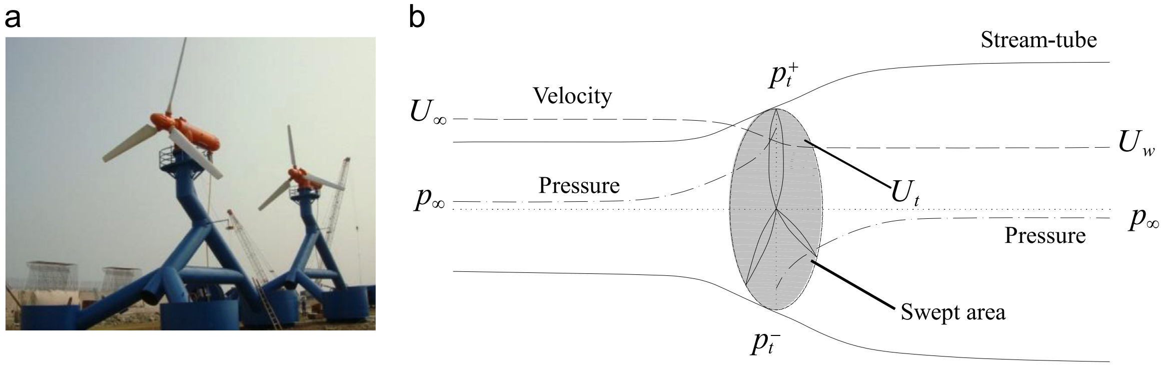

Fig. 2. The horizontal axis turbines deployed at southeast of Zhaitang Island for a test research (a) and the corresponding conceptual diagram of the energy extraction from tidal flow (b), the tidal currents from left to right (Roc et al., 2013).