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Design and performance enhancement of a bi-directional counter-rotating type horizontal axis tidal turbine

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ABSTRACT

A bi-directional counter-rotating type horizontal axis tidal turbine (HATT) consisting of fully symmetrical hydrofoils was designed to convert tidal energy in terms of ebb and flood tides. In CFD simulations, the counter-rotating rotors perform much more excellent power coefficient than single rotor. However, as the limit of application of fully symmetrical hydrofoils with low lift-drag ratio, the performance of bi-directional HATTs is much lower than traditional HATTs. In this work, multi-objective optimization method was employed to obtain a series of fully symmetrical hydrofoils applied to different sections from blade root to tip. The numerical results show that the application of optimized hydrofoils brings about considerable increment in power efficient (a relative increase 8% at BEP) and flow separation around hydrofoil.

1. Introduction

As the strong promotion of development of novel and economical renewable energy sources, ocean energy has seen a great increase in interest over recent years. The forms of ocean energy can be categorized into waves, tidal range, tidal currents, ocean currents, ocean thermal energy conversion and salinity gradients, each with different origins and requiring different technologies for conversion (Ellabban et al., 2014). Among them, tidal current energy caused by the combined effects of gravitational forces exerted by the Moon, Sun, and rotation of the Earth, is recognized as a most predictable sustainable resource that can be extracted and used for the purpose of commercial power generation (Blunden and Bahaj, 2006; Rourke et al., 2009; Lim and Koh, 2010; O'Rourke et al., 2010; Nasir et al., 2012).

To capture the energy of tidal currents, the horizontal axis tidal turbine (HATT) can be employed, operating in much the same manner as the horizontal axis wind turbine (HAWT) (Ben Elghali et al., 2007). In the literatures, there exist numerous studies on the performance of unidirectional HATTs, via theoretical analysis, model tests and full scale trials. The blade element momentum theory (BEMT) which is widely applied in the design of HAWTs has also been well employed to the hydrodynamic design of HATTs (Batten et al., 2008; Goundar and Ahmed, 2013; Singh and Choi, 2014). In order to verify the accuracy of theoretical analysis, Batten and Bahaj et al. Batten et al., (2007; Bahaj et al., 2007; Bahaj et al., 2007) performed a series of experimental investigations on the hydrodynamic performance and cavitation performance of an 800 mm diameter model tidal turbine in a cavitation tunnel and a towing tank. Clarke (Clarke et al., 2007) designed a contra-rotating tidal current turbine using the modified BEMT and conducted the model tests in a towing tank. The testing results demonstrated that a contra-rotating turbine with near-zero reactive torque on the support structure, near-zero swirl in the wake, and high relative inter-rotor rotational speeds can operate successfully. Marine Current Turbines (MCT) Ltd (SEAFLOW, 2005) installed a two-bladed turbine capable of generating 300kWoff the Devon coast near Lynmouth in May 2003, which is the world's first tidal current turbine in open sea conditions although not grid-connected. And by 2008 they had a 1.2 MW turbine, SeaGen, in Strangford Lough, Northern Ireland which was able to feed electricity into the National Grid.

As one might expect, tidal currents in terms of ebb and flood tides are bidirectional. Therefore, HATTs need to be designed to operate in both directions. As summarized in Liu's works (Liu and Bose, 2012; Liu et al., 2014), there are three basic configurations for tidal turbines to work in bi-directional currents: 1) Unidirectional turbine with fixed pitch blades operating in alternating orientations (at about 180°) so that it always faces the current; 2) Bi-directional turbine with a unidirectional blade section by reversing blade pitch angle (180°); and 3) Bi-directional rotor with a fully symmetrical blade section that operates identically in both tidal flow directions with the shaft rotating in opposing directions. The AR-1000 designed by Atlantis Resources

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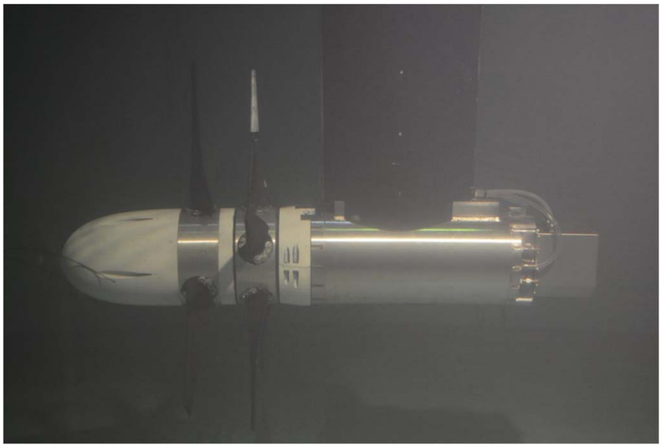

Fig. 1. Photograph of unidirectional counter-rotating type HATT.

Corporation can be rotated in the slack period between tides using a yaw drive, and then fixed in place for the optimal heading for the next tide (http://atlantisresourcesltd.com/turbines/ar-series/ar1000.html). The HS1000 designed by Andritz Hydro Hammerfest was equipped with a specially designed pitching system allowing optimal harnessing of tidal currents in both ebb and flood directions (http://www.andritz.com/hy-hammerfest.pdf). The HyTide designed by Voith Ocean Current Technologies used symmetric blade profile for bidirectional operation avoiding pitch and yaw requirements (http://voith.com/de/Ocean-Current_screen.pdf). All three of these designs which are rated at 1 MW and feature a 3-bladed rotor in the range of 16–21 m diameter have been installed and tested at the European Marine Energy Centre Ltd. (EMEC) in Orkney, Scotland.

The unidirectional counter-rotating type HATT as shown in Fig. 1 has been systematically studied in precious works (Huang and Kanemoto, 2015; Huang and Kanemoto, 2015; Huang et al., 2016). In the present work, a bi-directional counter-rotating type HATT sharing the advantages of bi-directional and counter-rotating type turbines was designed. A fully symmetrical hydrofoil based on the NACA16-015 was selected as the original blade element for every section of the blade from the root to the tip. And then the multi-objective optimization algorithm was employed to increase the lift-drag ratio of the original hydrofoil. CFD simulations were also conducted to verify the performance enhancement of the bi-directional counter-rotating type HATT constituted by the optimized hydrofoils.

2. Design of bi-directional counter-rotating type HATT

As the bi-directional counter-rotating type HATT designed in the present work operates in both tidal flow directions eliminating both yaw and pitch mechanisms, the hydrofoil adopted should be fully symmetrical in the suction side, pressure side, leading edge and trailing edge. In the preliminary design, the original fully symmetrical hydrofoil was developed from the NACA16-015 which is symmetrical and whose maximum thickness appears at 50% chord as shown in Fig. 2. It should be noted that the original fully symmetrical hydrofoil consists of the first half of NACA16-015 and its mirror portion.

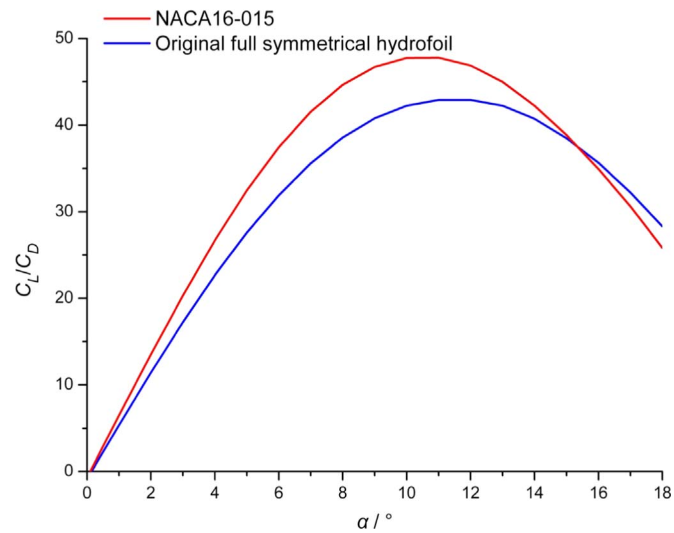

Fig. 3. Comparison of lift-drag ratios between NACA16-015 and original fully symmetrical hydrofoil.

The performance of NACA16-015 and original fully symmetrical hydrofoil is illustrated in Fig. 3. It is clear that the performance of original fully symmetrical hydrofoil decreases slightly because the trailing edge was enlarged.

A 3-bladed model bi-directional counter-rotating type HATT with the diameter of 500 mm was selected as a trade-off between maximizing the Reynolds number and not incurring excessive tunnel blockage correction. The blade pitch angle and chord distributions which obtain best efficiency at λ=3.5 designed by the traditional BEMT were shown in Fig. 4. The hub diameter and the distance between the front blade and the rear blade are 90 mm and 160 mm, respectively. The three-dimensional isometric view of the model counter-rotating type tidal turbine equipped with the blade designed here, is shown in Fig. 5.

3. Performance of original blade profiles

CFD analysis was carried out in ANSYS CFX 14.0 to predict the performance of the model bi-directional counter-rotating type HATT designed above. The cross-section of the computational domain has a width of 1500 mm (3*D*) and a depth of 1000 mm (2*D*). According to the domain length sensitivity study carried out by Nicholas A. G. Osbourne (Nicholas, 2015), the length of the computational domain was set to 10*D*, in which 3*D* and 7*D* for upstream and downstream of the front blade respectively. The model turbine was placed centrally in the domain with a tip immersion depth of 250 mm (0.5*D*). The computational domain consisted of three parts: the front rotor, the rear rotor and the stator. Either rotor domain was set to 40 mm upstream and 40 mm downstream of the rotor plane, as well as a diameter of 550 mm (1.1*D*).

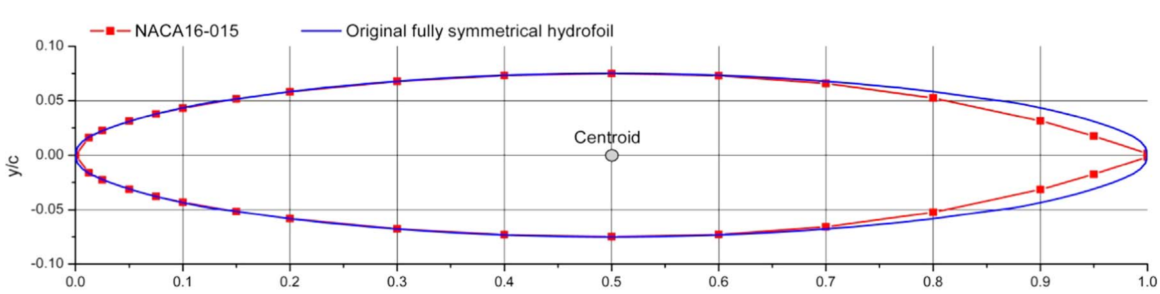

Fig. 2. Original fully symmetrical hydrofoil developed from NACA16-015.