Renewable Energy 81 (2015) 837–844

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Multi-objective numerical optimization of the front blade pitch angle distribution in a counter-rotating type horizontal-axis tidal turbine

B. Huang*, T. Kanemoto

Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu, Japan

ARTICLE INFO

Article history:
Received 30 October 2014
Accepted 2 April 2015
Available online 22 April 2015

Keywords:
Tidal stream
Counter-rotating
Multi-objective numerical optimization

ABSTRACT

In order to exploit renewable energies from tidal stream, tandem propellers of a unique counter-rotating type horizontal-axis tidal turbine was firstly designed based on the blade element momentum (BEM) theory. And then a multi-objective numerical optimization method coupled the response surface method (RSM) with the genetic algorithm (GA) was employed to obtain desirable blade profiles. The front blade pitch angle distribution was taken as optimization variable in this paper, as it plays an important role in affecting the inlet conditions of the rear blade. The numerical results show that both optimization objectives of power coefficient and thrust coefficient can be significantly improved. It was verified that the performance of the power unit with the optimized blades increases obviously by optimizing the pitch angle.

1. Introduction

For the next leap in the power technologies to get the sustainable society, it is required not only to cope with the warming global environment but also to conserve the natural ecosystem and coexist with the nature. Exploitation of the renewable green energy has attracted growing interest all over the world. Among the renewable energy resources, tidal current energy shows attractive potential when a cost-effective turbine of capturing this energy could be developed to conquer the harsh environment [1]. Horizontal-axis tidal turbines (HATTs) may be most effective to get the enough power among various types of tidal turbines [2].

Much of the design theory and technology associated with HATTs have been derived from the wind industry due to their similar working principles [3]. Nevertheless, there are some different characteristics such as the effects of the free surface, the different levels of velocity and turbulence, the different stall characteristics as well as the occurrence of cavitation which should be taken into consideration in the design process of a tidal turbine [4]. The blade element momentum (BEM) theory has been proven to be well established for modeling rotor dynamics of not only wind but also marine propellers [5]. Recently, Batten and Bahaj et al. [6–9] have employed the developed BEM theory to the hydrodynamic design of marine current turbines, which shows good agreement between the numerical results and experimental data obtained from tests of an 800 mm diameter model rotor carried out in a cavitation tunnel and a towing tank.

The results from BEM models are greatly influenced by the airfoil/hydrofoil data and dependent on empirical corrections to two dimensional (2D) airfoil/hydrofoil results to account for three-dimensional (3D) effects, such as tip loss, radial flow, and dynamic stall. Especially the blades for the counter-rotating type power unit, BEM theory seems incapable to simulate the mutual effects between the front and the rear propellers. Multi-objective numerical optimization method coupled with the response surface method (RSM) and the genetic algorithm (GA) has been recommended to provide for the optimization of the original blades designed by BEM theory, as it has been proven to be successful in the design of wind turbines [10,11] and tidal turbines [12].

This paper optimizes a counter-rotating type horizontal-axis propeller installed in the model tidal turbine as shown in Fig. 1. It was firstly designed according to the blade element momentum (BEM) theory. In the optimization process as the next step, the cubic Bezier curve with 4 control points was employed to get the desirable pitch angle distribution of the front blade. Subsequently, the Box–Behnken experimental design method (BBD) coupled with the CFD simulations and the response surface method (RSM) were used to obtain the quadratic polynomial regression equations of power coefficient and thrust coefficient. Finally, the optimization was carried out using the NSGA-II multi-objective genetic algorithm (GA).

* Corresponding author. Tel.: +81 90 9652 7939; fax: +81 93 884 3025.
E-mail address: huang.bin404@mail.kyutech.jp (B. Huang).

http://dx.doi.org/10.1016/j.renene.2015.04.008
0960-1481/

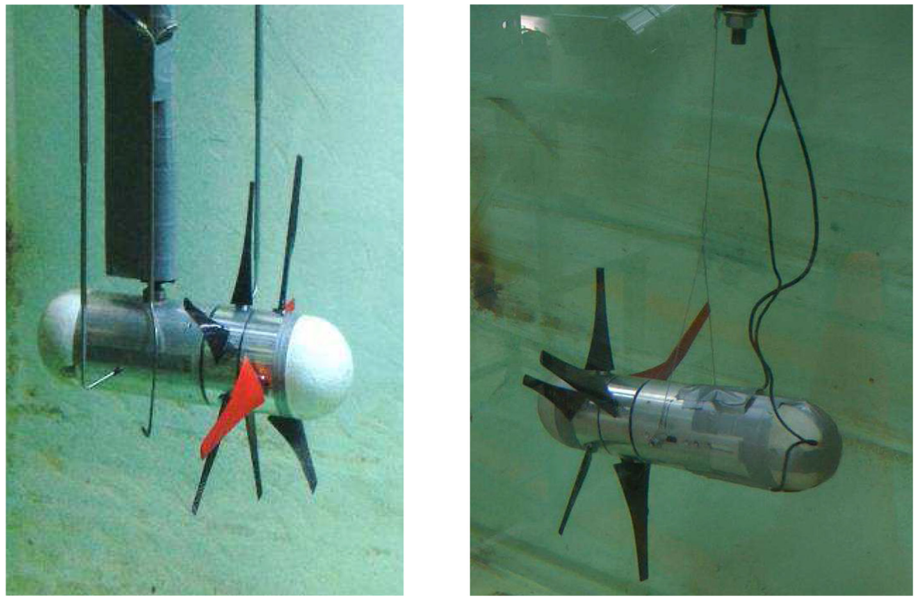

Fig. 1. Photograph of the model counter-rotating type horizontal-axis tidal turbine.

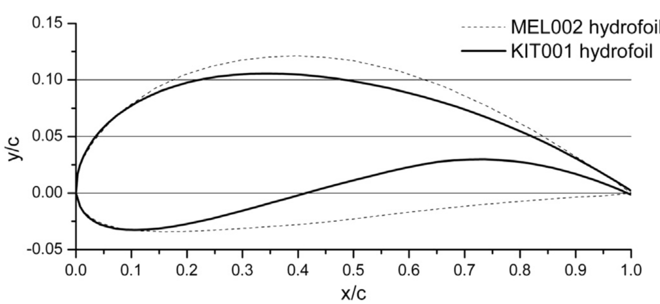

Fig. 2. MEL002 hydrofoil and KIT001 hydrofoil.

2. Preparation of the original blades designed by BEM

The general BEM theory is based on a combination of momentum and blade element theories [9,13,14], which is not mentioned in detail herein. In the present paper, the newly developed KIT001 hydrofoil derived from MEL002 hydrofoil, with higher lift-drag ratio was selected as blade elements as shown in Fig. 2.

The blade pitch angle and chord distributions of the original blades with blade element KIT001 optimized just above are shown in Fig. 3. In the model power unit, the diameter of the front propeller is $d_F = 500$ mm and the rear rotor is $d_R = 420$ mm, namely the diameter ratio [$=d_R/d_F$] is 0.84. The number of blades for the upstream/front and the downstream/rear propellers is $Z_F = 3$ and

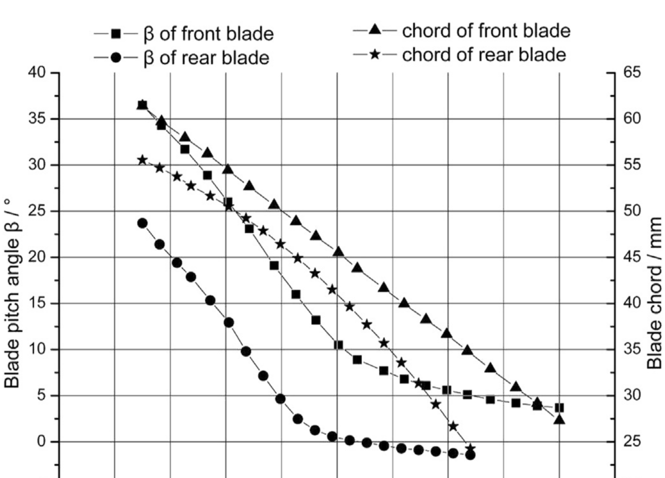

Fig. 3. Blade pitch angle and chord distributions of the original blades.

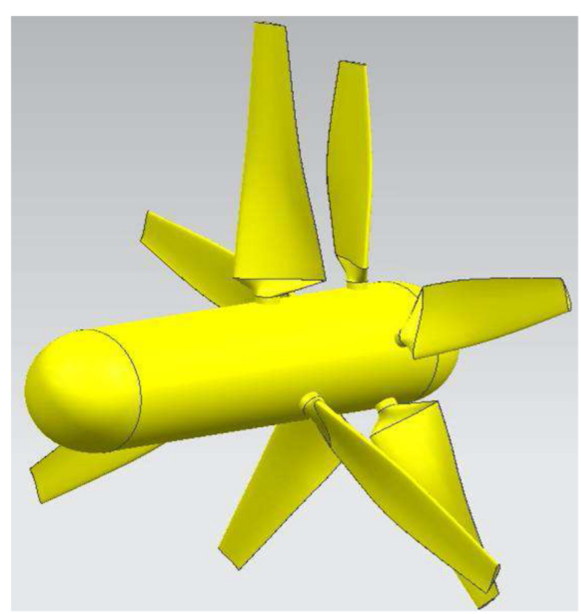

Fig. 4. Model counter-rotating type tidal turbine with the original blades.