Applied Ocean Research 79 (2018) 113–122

Contents lists available at ScienceDirect

Applied Ocean Research

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

Theoretical vertical-axis tidal-current-turbine wake model using axial momentum theory with CFD corrections

Yanbo Ma[a,b], Wei Haur Lam[a,b,*], Yonggang Cui[a,b], Tianming Zhang[a,b], Jinxin Jiang[a,b], Chong Sun[a,b], Jianhua Guo[a,b], Shuguang Wang[a,b], Su Shiung Lam[c], Gerard Hamill[d]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, People's Republic of China
[b] First R&D Services, A-08-16 M Suites, 283 Jalan Ampang, 50450 Kuala Lumpur, Malaysia
[c] Pyrolysis Technology Research Group, Eastern Corridor Renewable Energy Group (ECRE), School of Ocean Engineering, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[d] School of Natural and Built Environment, Architecture, Civil & Structural Engineering and Planning, Queen's University Belfast, David Keir Building, Stranmillis Road, Belfast BT9 5AG, United Kingdom

ARTICLE INFO

Keywords:
Ocean engineering
Ocean energy
Marine renewable energy
Vertical-axis turbine
Tidal current turbine
Wake model

ABSTRACT

The wake from a tidal current turbine has a significant impact on a tidal farm. A single turbine wake would affect the turbine located adjacent or downstream. Two equations are proposed to predict the mean velocity within the wake of a vertical-axis turbine. The first equation used to predict the efflux velocity is derived based on the axial momentum theory and dimensional analysis. Efflux velocity is the minimum velocity closest to the turbine downstream. The second equation used to predict the lateral velocity distribution is derived based on Gaussian probability distribution. The predictions are compared with the existing experimental and numerical results. Validation of the equations gives a variation in the range of 0–1.13% for the efflux velocity by comparing the proposed theoretical works and Dai and Lam's experimental measurements. These equations are the foundation of the analytical method for wake prediction of a vertical-axis turbine.

1. Introduction

The heavy use of fossil fuels is exacerbating environmental pollution and climate warming with the development of the world economy. Researchers investigate the replacement using renewable energy and proposed that marine renewable energy has great potential due to its broad ocean areas [1]. Harnessing marine renewable energy is challenging due to the harsh operating condition in ocean. In general, marine renewable energy includes ocean tides, ocean waves, tidal current, temperature gradient and salinity gradient energy [2]. Ocean wave energy is the energy of moving and elevated water within a wave. Tidal and current energy is the kinetic energy in moving water, such as ocean current stream or tidal current. Ocean thermal energy is the energy recoverable in the temperature gradient between the warm surface water and the cold deep water. Salinity gradient energy is the energy obtained from the salinity gradient between the waters from different regions. Tidal current energy has made good progress these years, among the aforementioned five forms of marine renewable energy, owing to its predictability and higher density of water compared to wind. Tidal current energy is the potential types of marine renewable energy and is expected to give significant contribution to future mix of the energy supply [3].

Tidal current turbine is the essential device used to harness the kinetic energy from the tidal current. Incoming flow leads to the rotation of turbine and the induced torque forces due to rotation is being transferred to the generator for electricity. Rotating turbine disturbs the incoming water flow producing the wake downstream. The wake behind a tidal current turbine has significant impact on the velocity field downstream. A tidal current turbine could extract kinetic energy of flowing water and induce a velocity deficit downstream. The velocity deficit influences the performance of turbines in tandem that the overall efficiency of the turbine array will be affected. Thus, wake properties of a tidal current turbine should receive more attention and the theory of tidal current turbine wake need to be developed. Experimental, numerical and theoretical methods should be taken to understand the tidal current turbine wake.

Generally, researchers focus more on the efficiency of turbine instead of the wake of turbine. Wei et al. conducted a series of experiments to investigate the influence of blade pitch angle and axial distance on the performance of the counter-rotating type horizontal-axis

* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, People's Republic of China.
E-mail address: wlam@tju.edu.cn (W.H. Lam).

https://doi.org/10.1016/j.apor.2018.07.016
Received 6 March 2018; Received in revised form 3 July 2018; Accepted 29 July 2018

tidal turbine and found that the proper increase of blade pitch angles and axial distance could enhance the performance of a counter-rotating turbine by increasing the peak power coefficient value and widening high power coefficient value area [4]. Liu et al. used both analytical and numerical methods to predict the effects of blade twist and nacelle shape on the performance of horizontal axis tidal current turbines [5]. Wang et al. analysed how the yawing frequencies affect the main hydrodynamic coefficients of the turbine [6]. Liu et al. conducted experimental model tests to predict the performance of two sets of metal and plastic bidirectional tidal turbine rotors [7]. The numerical results showed that the application of optimised hydrofoils improve the power efficiency with better flow separation around hydrofoil. However, the research on turbine efficiency is connected to the understanding of the surrounding flow field. Flow field investigation is also required to understand the wake structure. The investigation of velocity field within a turbine wake is therefore significant to increase the overall performance of tidal turbine farm.

Recently, researchers conducted experiments to investigate velocity within a turbine wake. Atcheson et al. conducted an experiment to measure the performance and wake characteristics of a 1:10th scale horizontal-axis turbine in steady uniform flow conditions, and found that increasing the inflow velocity from 0.9 m/s to 1.2 m/s influenced the turbulent wake characteristics more markedly and the flow field in the wake of a horizontal-axis tidal turbine is strongly affected by the turbine support structure [8]. Wang proposed the energy coefficient factor to include the tip speed ratio and solidity of turbine to better predict the velocity field within a horizontal-axis turbine wake [9]. Seo et al. conducted model tests for power and wake measurements in a towing tank facility to investigate conversion of kinetic energy of the turbine wake and decomposed it into effectively extracted work, loss due to the drag on the turbine system, kinetic energy of the time-mean axial flow, local flow structures, turbulence, and secondary flow loss [10]. Experimental methods are important to obtain the data of the velocity within the wake of the tidal current turbine.

Numerical simulations also be applied to predict turbine wake properties. Sufian et al. made a CFD model to simulate impacts from a horizontal-axis tidal turbine under combined surface waves and a steady current. Results showed that the wave-period-averaged velocities were similar to those in the steady-current-only condition [11]. Mohammad et al. used the hybrid LES/ALM technique to investigate the wake of a laboratory scale tidal stream turbine in a shallow water channel, it revealed that the distinct characteristics of the streamwise changes of turbulence intensity or turbulent kinetic energy might serve as an effective indicator for the flow regime transition and wake behaviour [12]. Bromm et al. performed simulations to investigate the impact of directionally sheared inflow on the wake development behind a single wind turbine and to analyse the impact of the wakes on the energy yield and loading of a downstream turbine [13]. Results showed that directionally sheared inflow led to a non-symmetrical wake development, which transferred to distinct differences in the energy yield and loading of downstream turbines of equal lateral offsets in opposite direction. Numerical simulation is another method to study on the wake of the tidal current turbine.

As for theoretical equations to predict a turbine wake, Lam et al. proposed two equations to predict velocity within a horizontal-axis turbine wake. One is used to predict the efflux velocity of a turbine wake, which is based on the axial momentum theory [14]. The other one is used to predict the lateral velocity distribution downstream, which is based on Gaussian probability distribution. These equations could accurately predict velocity within a horizontal-axis turbine wake. However, no equation is available to predict velocity within the wake of a vertical-axis turbine. Theoretical equations are convenient for engineers to investigate the basic condition of the wake of a tidal current turbine quantitatively. This research proposes the theoretical equations which could predict velocity within a vertical-axis turbine wake.

2. Methodology

Methodologies include the axial momentum theory to deduce the equation and computational fluid dynamics (CFD) methods to conduct the numerical simulation. The axial momentum theory is the theoretical foundation of the deduction of the efflux velocity. Computational fluid dynamics (CFD) methods are used to understand the velocity distribution of the wake. Both of axial momentum theory and CFD are to proposed the theoretical equations for vertical-axis turbine wake.

2.1. Axial momentum theory

Froude proposed the axial momentum theory which was based on Rankine's research. The axial velocity component is the most important velocity component of a propeller wake. Tangential velocity component and radial velocity component of wake are smaller compared to the axial velocity component and their effect on wake is less significant. Axial momentum theory takes only the axial velocity component into consideration on the basis of actuator disc model. This model was used to develop the theoretical model for propeller wake. The axial momentum theory has been widely used to predict the efflux velocity of ship propeller wake and the horizontal-axis turbine wake, which includes the following 6 assumptions.

(1) The turbine can be simulated with an ideal equal diameter actuator disc.
(2) The actuator disc is composed of numerous rotating blades, and the blades rotate at an infinite speed.
(3) The thickness of the actuator disc is negligible in the axial direction.
(4) The actuator disc is undisturbed in the ideal fluid (for non viscous fluid);
(5) The fluid is subjected to the same increase of pressure when the fluid flows through the disc.
(6) The energy supplied to the disc can be completely converted into the fluid without any rotation effect.

The axial momentum theory has been widely used to describe the characteristics of ship propeller jets. Albertson et al. studied the velocity field of a jet based on the axial momentum theory [15]. This works were adapted to be the foundation of all propeller jet researches. Blaauw & van de Kaa, Berger and Verhey et al. agreed that the propeller jet flow consisted of axial, tangential and radial velocity components [16–18]. Hamill et al. used physical propellers to investigate the velocity field of the propeller jet with consideration of the rotation characteristics of the propeller rather than a plain water jet [19–21]. On this basis, Lam observed the flow field distribution of a propeller jet by using the Laser Doppler Anemometry (LDA). The effect of axial velocity, tangential and radial velocity components of the propeller jet is revealed through further investigation using the CFD numerical simulation [22]. Lam innovatively applied the axial momentum theory to the field of the tidal current turbine. The equations proposed by Lam could predict the velocity within the wake of a horizontal-axis turbine. In this paper, the axial momentum theory is used to propose the equations used to predict the velocity within the wake of a vertical-axis turbine [23].

2.2. CFD corrections for wake model

Partial differential equations are usually used to describe the physical properties of fluid flow. The equations which govern the flow of the fluid are called governing equations. Computational Fluid Dynamics (CFD) can solve the governing equations of fluid mechanics using computer and numerical methods. CFD can also simulates and analyses problems of fluid flow, heat transfer and related transfer. The governing equation for the flow at the macroscopic scale is called the Navier-Stokes equation, which is mainly composed of the continuity equation,