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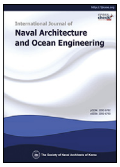

Numerical simulations of a horizontal axis water turbine designed for underwater mooring platforms

Wenlong Tian [a,b,*], Baowei Song [a], James H. VanZwieten [b], Parakram Pyakurel [b], Yanjun Li [c]

[a] *School of Marine Science and Technology, Northwestern Polytechnical University, 710072 Xi'an, Shaanxi, China*
[b] *Southeast National Marine Renewable Energy Center, Florida Atlantic University, 33431 Boca Raton, FL, USA*
[c] *College of Engineering, Florida Atlantic University, 33431 Boca Raton, FL, USA*

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Abstract

In order to extend the operational life of Underwater Moored Platforms (UMPs), a horizontal axis water turbine is designed to supply energy for the UMPs. The turbine, equipped with controllable blades, can be opened to generate power and charge the UMPs in moored state. Three-dimensional Computational Fluid Dynamics (CFD) simulations are performed to study the characteristics of power, thrust and the wake of the turbine. Particularly, the effect of the installation position of the turbine is considered. Simulations are based on the Reynolds Averaged Navier-Stokes (RANS) equations and the shear stress transport k-ω turbulent model is utilized. The numerical method is validated using existing experimental data. The simulation results show that this turbine has a maximum power coefficient of 0.327 when the turbine is installed near the tail of the UMP. The flow structure near the blade and in the wake are also discussed.

Keywords: Horizontal axis water turbine; HAWT; Computational fluid dynamics; CFD; Hydrokinetic energy

1. Introduction

Underwater Mooring Platforms (UMPs) are a class of underwater devices that are anchored to the seabed using mooring cables. This device type can perform numerous functions, with expected performance durations typically ranging from months to years.

Common UMPs include subsurface buoys (oceanographic sensors, acoustic communication nodes, etc.), moored mines and self-mooring autonomous underwater vehicles (AUVs) (Robert, 2010). Currently, most UMPs are battery-powered and because of their finite energy supply and the uninterrupted consuming of energy by the onboard electronic devices, stored energy limitations typically limit the duration of their installed operation. For example, the M-3 moored mine can only work for 12 months before the installed batteries runs out of power (Andrew et al., 2009). Extending the operational life of UMPs can significantly reduce the cost for missions where a sustained presence is require, because of the high costs associated with retrieving, repowering, and redeploying remote systems.

To nearly eliminate the need for redeploying UMPs due to power limitations energy can be extracted from renewable resources to recharge the batteries of these platforms. To our best knowledge, four kinds of ocean energy, including ocean surface solar energy, ocean thermal energy, ocean wave energy, and ocean current energy has been used to power ocean devices.

The Solar-powered AUVs (SAUVs) are a series of underwater vehicles powered by solar energy (Crimmins et al., 2006; Jalbert et al., 2003). The power system consists of a solar panel, microprocessor, battery gas gauge, charge controller and battery stack. These systems are designed for

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* Corresponding author.
E-mail address: tianwenlong@mail.nwpu.edu.cn (W. Tian).
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long duration missions such as monitoring, surveillance and station keeping. Since these vehicles must surface for recharging it is infeasible to use this method to recharge the UMPs.

Researchers have also tried utilizing ocean thermal energy to propel underwater gliders (Webb et al., 2001). However, energy density of the ocean thermal energy is very low and the vehicle must follow saw-tooth-liked trajectories that transient through a thermocline to gain enough energy. Therefore ocean thermal energy utilization is not suitable for UMPs which are expected to perform fix-point monitoring underwater.

Ocean wave energy has been used to power ocean sensor buoys (Jeannette, 2015). The Direct Drive System employs small electric generators that are directly driven via a surface buoy's wave-induced heave motion. However, motion in the water below a deep-water wave is vertically attenuated, that is, the horizontal and vertical velocities decrease with depth exponentially (Benoit, 2014). To maximize the generated power, the conversion device must be installed near the sea surface. Like the solar energy, wave energy is not suitable for proving power to most UMPs.

UMPs are often deployed where ocean currents are consistently available. The kinetic energy available in ocean current provides an ideal alternative to recharge the UMPs. Wenlong et al. designed a miniature vertical axis water turbine (VAWT) with controllable blades to generate the ocean current turbine and recharge a moored AUV (Wenlong et al., 2013). This turbine is similar in design to the Darrieus turbine when expanded. However, due to the disturbance of the hull of the AUV, the efficiency of the turbine was low and the maximum coefficient of the averaged power was found to be 0.1 (Wenlong et al., 2013).

Water turbines, which have been widely used for hydrokinetic power generation, can be classified into two categories depending on the orientation of turbine axis with regard to the water flow direction. The vertical axis water turbine (VAWT), also known as the cross-flow water turbine, rotates around an axis perpendicular to the current. Conversely, the horizontal axis water turbine (HAWT) has an axis of rotation parallel to the current direction. This type of turbine typically has a propeller-type design with two or three blades with rotational torque created by the lift generated on the blades. VAWTs are typically less efficient when compared with their horizontal counterparts, and have been show to achieve poor performance when utilized on UMPs (Wenlong et al., 2013).

Experimental trials on HAWTs have been carried out by many researchers. Bahaj et al. (2007a,b) carried out a power and thrust coefficient study on a 0.8 m-diameter turbine in a towing tank and in a cavitation tunnel. They provided comprehensive high-quality data for the validation of numerical computations. Coiro et al. (2006) conducted towing tank experiments of a scaled model of an HAWT and provided the power and thrust curves at different water velocities. Galloway et al. (2011) studied the power and thrust performance of a 1/20th scale HAWT operating at yaw and in waves by performing towing tank experiments. Tedds et al. (2011) provided many turbine performance curves depending on the number of blades, pitch angles, etc. Recently, Mycek et al. (2014a,b) studied the upstream turbulence intensity effect and the interaction between two turbines, with emphasis paid on the wake of the turbine.

To predict the performance of HAWT numerical methods have also been utilized. Blade element momentum methods (BEM) have been used widely for engineering design because of their low computational cheap and high efficiency. During the past years, BEM method has been improved to account for three-dimensional (3D) effects by introducing new correction models such as tip loss (Shen et al., 2005), rotational flow (Burton et al., 2001) and dynamic stall (Leishaman, 1989). 3D inviscid models provide more physics of the turbine hydrodynamics than the BEM method. Current 3D inviscid models include lifting line (Epps et al., 2009), panel (Liu, 2010), and vortex-lattice (Lei et al., 2013). However, these methods neglect the viscous effects, which need to be considered to achieve the most accurate turbine performance predictions possible.

Computational fluid dynamics (CFD) simulations of the Navier−Stokes equations model fluid flows starting from first principles, and therefore inherently capture viscous effects. Comprehensive CFD simulations of horizontal axis water/wind turbines have been done. Michael et al. computed a 20 m-tidal turbine at different flow velocities using the commercial CFD code STAR CCM+ to investigate the effect of grid density and time step on the calculated torque (Michael et al., 2011). Monier et al. (2013) designed and optimized a winglet for the NREL Phase VI turbine using the Fine/Turbo of the commercial CFD code NUMECA. They provided a detailed CFD validation study of the NREL Phase VI turbine (Hand et al., 2001) showing that the CFD results were in good agreement with the experiment results. Yuwei et al. (2012) carried out CFD simulations of the NREL Phase VI turbine with both unsteady Reynolds-Averaged Navier−Stokes (RANS) and Detached Eddy Simulation (DES) methods. Tongchitpakdee et al. (2005) studied the aerodynamic performance of the NREL Phase VI horizontal axis wind turbine under yawed flow conditions. More recently, Nak et al. (2015) studied the effect of the distance between dual rotors on the performance and efficiency of a counter-rotating tidal turbine using both CFD and experimental methods.

In order to improve the poor power performance of the previous turbine design used for UMPs (Wenlong et al., 2013), a HAWT has been designed that can be installed on UMPs. This paper focuses on the CFD simulations of this turbine design. The study is performed using the finite volume code FLUENT 13.0 with a Rotating Reference Frame (RRM) model. The effect of the installation position on the output performance of the turbine is studied over a range of tip speed ratios (TSRs).

2. Description of the HAWT

The UMP considered in this study is a self-mooring AUV. The self-mooring AUV is expected to travel to a desired mooring location, moor itself on the seafloor, collect