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Experimental and numerical characterization of a full-scale portable hydrokinetic turbine prototype for river applications

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ABSTRACT

A preliminary hydrokinetic turbine prototype for river applications was built for experimental testing at the circulating water channel at the Naval Surface Warfare Center, Carderock Division. The prototype was designed based on numerous blade characterization and optimization analyses conducted using computational fluid dynamics (CFD) simulations. Testing was conducted for channel flow speeds ranging from 1.0 m/s to 1.7 m/s. At each tested flow speed, the generator loading was manually adjusted to produce a performance curve based off the power output from the prototype unit. In addition to manual generator loading, a solar charging unit was used to simulate turbine operation while adjoined to the ground renewable energy system (GREENS). CFD predictions were produced for the prototype using the k-ω SST turbulence model for the purpose of validation. A peak power coefficient of 0.37 was measured at a tip speed ratio of 2.50 during manual generator loading. Relative error between numerical predictions and experimental results was less than 3.0% when generator, transmission, gearbox, and other losses of selected components were applied to the numerical predictions. The solar charging converter improved prototype operation by conditioning the power output, indicating that the prototype could successfully be integrated with GREENS for portable applications.

1. Introduction

Hydropower currently yields 78 GW of energy production, per year, amounting to roughly 8% of the total electricity generating capacity of the U.S. [1]. Hydrokinetic marine current turbines (MCT) use kinetic energy from streams, rivers, and tides to drive a rotor and generate electricity. Hydrokinetic technologies are advantageous in that they require minimal civil structures for implementation compared to conventional hydropower. Current estimates for recoverable hydrokinetic energy are approximately 120 TWh/yr in United States and represent a majority of untapped hydropower resources [2]. Hydro power technology is advantageous to supply sustainable source of electricity for remote regions having water sources such as South Africa and South America. Kusakana et al. [3] performed a case study for South Africa to determine the possibility of sustainable electricity generation through hydrokinetic turbines. They compared the performance of proposed hydrokinetic turbine to other power generation systems such as wind turbine, diesel generator and standalone photovoltaic system in terms of initial capital, energy cost, total present cost and the shortage of system capacity. They concluded hydrokinetic turbine system is a better option for regions having sufficient water sources.

Hydrokinetic turbine designs developed for river application are primarily limited to low free stream velocities observed for operation and limited depth; as a result, system size and potential for deployment is restricted. Data provided by United States Geological Survey (USGS) regarding free stream velocities and average depths of rivers in the U.S and respective territories indicate that many rivers in the United States have approximately three meters or less of average depth. When considering an operational range of free stream velocities from 0.75 m/s to 2.5 m/s, approximately 51.0% of all rivers are suitable for turbine deployment [4].

Mukherji et al. [5] .and Kolekar et al. [6–8] utilized blade element momentum (BEM) theory and computational fluid

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dynamics (CFD) analyses to optimize a horizontal axis hydrokinetic turbine rated for 12 kW. Goundar et al. [9] used a similar approach to design a marine current turbine rated for 290 kW. Performance characteristics study and structural finite element analysis of a micro hydrokinetic turbine with Archimedean spiral rotor were conducted by Riglin et al. [10] and Schleicher et al. [11]. Numerical design and characterization of a propeller-based micro hydrokinetic turbine were investigated by Schleicher et al. [12,13] and Riglin et al. [14]. Schleicher et al. [15,16] applied response surface methodology to design hydraulically efficient optimum hydrokinetic turbine. Riglin et al. [17–19] applied diffuser optimization for a micro hydrokinetic turbine and investigated the performance characteristics of two different diffuser designs having area ratio of 1.36 and 2.01.

Multiphase simulations were conducted for a micro-hydrokinetic turbine by Riglin et al. [20] to determine the performance of the unit operating close proximity to the free surface. Multiple array configurations of micro hydrokinetic turbines were studied by Riglin et al. [21] and Daskiran et al. [22] to determine the performance of adjacent units and the wake interaction influence on downstream turbine performance. The design introduced by Schleicher et al. [12,15,16] incorporated both a propeller structure and a higher value of solidity compared to observations in studies conducted with traditional hydrokinetic and marine current designs. The unit produced by Shleicher et al. [12] provided a benchmark maximum power coefficient of 0.43.

Experimental analyses of traditional designs were conducted by Kolekar et al. [8], Mycek et al. [23,24], and Bahaj et al. [25]. Performance results for two, inline units were obtained by Mycek et al. [23]and compared directly to single unit results [24]. Kolekar et al. [8] tested turbine operation in close proximity to the free surface and under increased blockage ratio for a scaled turbine model. Bahaj et al. [25] experimented on an 0.8 m diameter MCT in a towing tank allowing for power and thrust to be determined as well as the point of cavitation inception for different yaw and pitch angles.

This study highlights efforts made in producing a prototype of the non-traditional hydrokinetic turbine first introduced and optimized by Schleicher et al. [12,15,16]with characterization and prototyping efforts led by Riglin et al. [14,18–20] The main contribution of the current study is to conduct experimental analysis of a full scale hydrokinetic turbine system including runner, diffuser, nacelle and ellipsoid supports. The prior characterization and optimization numerical studies of the present authors were conducted without the presence of nacelle, ellipsoid supports and even diffuser for some of them. Experimental results were used to validate numerical predictions of an identical system operating under similar loading.

The present study of propeller-based hydrokinetic turbine differs from aforementioned experimental studies of traditional hydrokinetic turbines through its some features. Firstly, a diffuser was augmented to the turbine runner to enhance the system performance. The prototype is modelled and designed to be compact and easily person-portable. The developed hydrokinetic turbine system can simply be transported and installed in streaming water to generate power in a short time. The system was designed to integrate into the Ground Renewable Energy System (GREENS) allowing for tandem hydropower and solar power generation. Similar efforts have been made, including by Li et al. [26], to integrate solar and hydro energy conversion into a single system. The present body of work highlights both characterization of the hydrokinetic prototype through simple electrical loading as well as the implementation of a solar charging converter to mimic GREENS implementation. Testing was conducted at the circulating water channel (CWC) at the Naval Surface Warfare Center, Carderock Division. Results from both tests are used to validate pre-existing numerical predictions used in design, characterization, and optimization.

2. Prototype design

2.1. Blade design

The blade design incorporated in the prototype was originally generated by Schleicher et al. [12] using predetermined goals for output power, set operating conditions, and an empirical relationship of lift and drag for cascading flat plates generated by Cebrián et al. [27]. The final blade and diffuser geometries were optimized by Schleicher et al. [15,16] using rapid CFD processes and central composite design methodology. For the optimization of the final design, a full factorial experiment was conducted for a free stream velocity of 1.5 m/s. The flow speed was selected such that the turbine would be operable over the broadest range of applicable conditions for useful power generation as indicated by river data. Equations for blade generation, including blade angles, chord length, and wrap angle are included in [12].

For the actual prototype design, Schleicher [16] incorporated a B-spline in the rapid CFD optimization implemented allowing for blade curvature to improve predicted power and thrust outputs. The final propeller based blade design is shown in Fig. 1 with the wrap angle ($\Delta\theta$), blade angle (β'), relative flow angle (β) to the turbine's rotating frame of reference, and meridional length (Δm) listed. The optimized B-spline to produce the curvature in the blade is shown in Fig. 2. This curvature leads to corresponding blade angle from the leading edge (LE) to the trailing edge (TE). The runner design observed Fig. 1 was augmented with a diffuser with an area ratio (AR) of 1.31. The values of diffuser length (L) and diffuser angle (θ) for the implemented part were 0.381 m and 12°, respectively. The full list of turbine and diffuser design parameters incorporated in the final design are provided in Table 1.

The full turbine-prototype design is detailed below in Fig. 3 with assembled nacelle, hub, elliptical supports, blades, and diffuser geometries. The inlet of the overall system can be observed in Fig. 3a. The role of the diffuser and leading cone expand beyond improved performance and in the present design serve as the primary structural supports of the overall system. The diffuser is the primary component of the entire unit design. The nacelle has a slightly larger diameter and allows for the back end elliptical supports to be fixed perpendicular to the diffuser.

2.2. Mechanical-electrical power conversion

Based on the optimization work done by Schleicher, the design had a predicted output of approximately 431.4 W of mechanical power at a free stream velocity of 1.5 m/s. A 20 A, continuous DC permanent magnet generator produced by Windstream LLC was selected for mechanical-to-electrical power conversion. Utilizing a DC generator over AC options allowed for a broader range of flexibility for future GREENS interfacing. The generator output specifications along with the anticipated primary operating point at which the prototype is designed for is provided in Fig. 4. Under the present designed conditions, a 48 V DC output with a current of approximately 8 A would be observed under flow conditions of 1.5 m/s and a blade rotation rate of 115 RPM. The selected generator may only operate continuously at currents less than 10 A with a cutoff at 20 A. Due to the present limitations on the selected generator, operational free stream velocity is limited to roughly 1.9 m/s.

The rotation rate of the optimized turbine blade under ideal loading is 115 RPM. According to the operation point located in Fig. 4 the rotation rate of the generator shaft is approximately 1150