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Experimental study on kinetic energy conversion of horizontal axis tidal stream turbine

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ABSTRACT

The present study aims to understand the energy conversion mechanism of a 100 kW horizontal axis tidal stream turbine by analyzing thrust, torque, and wake flow measurements. The scale ratio of the turbine model was 1/20 and model tests for power and wake measurements were conducted in a towing tank facility. Wake fields were measured by a towed underwater stereoscopic particle image velocimetry (SPIV) system. The chord-length based Reynolds number at 40% of the radius of the turbine ranged from 53,000 to 63,000 in the test conditions. The turbine model showed the highest power coefficient at a tip speed ratio (TSR) of 3.5, and the magnitude of power coefficient was 0.278. Three TSR conditions were selected for SPIV measurement after power measurement tests, representing heavy loading, highest efficiency, and light loading, respectively. In the wake field measurement results, conversion of kinetic energy of the turbine wake was investigated, decomposing 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. In high TSR conditions with a small angle of attack onto the turbine blade, the secondary flow loss was minimized.

1. Introduction

Energy from marine currents offers the promise of regular and predictable electricity generation at higher power densities than other renewables [1]. Although there are various ways to capture hydrokinetic energy, the most common configuration is known as a horizontal axis tidal stream turbine (HATST), which resembles a small wind turbine. Ng et al. (2013) [2] have provided a comprehensive review of research on HATSTs from 2002 to 2012, which covers various aspects such as wakes, energy assessment, turbine design, and environmental impact. Even though HATSTs share many similarities with wind turbines, there are fundamental differences such as the range of Reynolds number, stall characteristics, the ratio of the turbine height to the boundary layer thickness, free surface effects, and the potential for cavitation [3]. The effects of these characteristics have been studied both experimentally and numerically, mainly focusing on the energy conversion performance, which has lately been a topic of particular interest (for example, see Ref. [4] and references therein).

Flow field measurements in the wake behind a turbine are required to further understand the power extracting mechanism from a tidal turbine and interaction effects between flow and a turbine. Wind turbine wakes have been studied extensively through both laboratory-scale and full-scale turbines and are the subject of a great deal of literature (for example, see Refs. [5–7]). Whereas, wakes downstream of HATSTs have been investigated to a much lesser extent. In recent years, some laboratory experiments have been conducted to examine wake characteristics downstream of a HATST. Tedds et al. (2014) [8] conducted experiments in a recirculating water flume to measure the wake fields downstream of a model HATST with a rotor diameter (D) of 0.5 m; 1.5D to 7D downstream of the rotor. They provided a systematic data set, including the velocity deficit, turbulence intensity, turbulent kinetic energy, and Reynolds stresses. High level Reynolds stress anisotropy was observed at less than 7D distance. Stallard et al. (2015) [9] investigated the wake generated downstream of a three-bladed rotor with a diameter of 0.27 m; 0.5D to 12D downstream of

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the rotor. According to their measurements, the process of mass and momentum mixing between turbine wake and the surrounding flow was observed in the downstream region after one rotor diameter from the rotor plane. Chamorro et al. (2013) [3] measured the wake of a miniature three-bladed HATST with a rotor diameter of 0.126 *m* using a volumetric three-component velocimetry (V3V) technique. They observed strong coherent tip vortices generated by the blades within the first rotor diameter downstream of the rotor plane. It is noted that wake stability is lost at distances greater than two rotor diameters.

The very-near wake is the region from the turbine to approximately one rotor diameter downstream, where the wake structure is preserved. That is, tip vortices instabilities such as short- and long-wave instabilities and mutual inductance instability are not observed (for a comprehensive description on the instabilities, refer to [10]). This region is highly associated with the performance of the turbine, as loss of kinetic energy in the very-near wake is mainly caused by energy extraction of the turbine, rather than turbulence dissipation and viscosity.

In this study, we aim to investigate the energy conversion mechanism of a model HATST by measuring the very-near wake. Experimental measurements were conducted in a towing tank at Seoul National University (SNU), and flow velocities in the very-near wake region were measured using an underwater stereo particle image velocimetry (SPIV) system. Our discussion concentrates on the conversion and loss of kinetic energy through the HATST, which is essential for understanding the energy extraction mechanism. The experimental setup and measurement methods are further detailed in Section 2 and 3. The results of the power and wake field measurement and energy conservation are analyzed and discussed in Section 4, and a summary and conclusions of this work are presented in Section 5.

2. Experimental setup and method

Experimental measurements were carried out in a towing tank at SNU. The towing tank, which is 110 *m* long, 8 *m* wide, and 3.5 *m* deep, is equipped with a speed-controlled towing carriage for speeds from 0.1 to 5.0 m/s with an error less than 0.05% of speed input. In bounded testing facilities such as wind and cavitation tunnel, the wall-induced blockage is a very important factor which affects the experimental results significantly. Such blockage effects have been investigated in many studies (for example, refer to [11–14]). On the other hand, towing tank experiments can be free of significant effects of wall interference. As discussed in experimental study of Bahaj et al. (2007) [15], towing tank tests are appropriate for precise tests on energy converting performance with small blockage effects. In our experiments, the ratio of turbine disk area to the towing tank cross-section was 0.45%. The blockage effect is a negligible problem in the present study.

Table 1
Geometry of the HATST model: distribution of chord length and pitch angle.

r/R	Chord length [mm]	Pitch angle [deg.]
0.3	34.2	16.98
0.35	32.8	14.59
0.4	31.3	12.66
0.45	30.0	11.07
0.5	28.4	9.75
0.55	27.0	8.64
0.6	25.5	7.69
0.65	24.1	6.87
0.7	22.6	6.15
0.75	21.1	5.50
0.8	19.7	4.91
0.85	18.3	4.33
0.9	16.8	3.74
0.95	15.4	3.02
1.0	13.9	2.50

In this study, we selected a 1/20 scale model of a 100 kW-class HATST, as used in the numerical simulations of Lee et al. (2012) [16]. A tower and nacelle of a full-scale system were excluded from the experimental model. The blades had a radius (R) of 200 mm and rotated in a counter-clockwise direction when looking downstream. As shown in Fig. 1, the turbine model had a rotor with three blades. The hydrofoil region of the blade ($0.3 < r/R < 1.0$) had a NACA 63–418 cross-section. The cross-section at the root of the turbine blades ($r/R = 0.15$) was elliptical. Therefore, a fitting between the ellipse and the NACA foil cross-section was placed in the adapting region ($0.15 < r/R < 0.3$). The pitch angle and chord length distribution along the radial direction of the blade is shown in Table 1.

A dynamometer, having maximum thrust of 100 *N*, maximum torque of 5 Nm, and maximum revolution rate of 25 revolutions per second (*rps*), was installed onto the towing carriage to measure thrust and torque acting on a turbine model in operation. Measurement signals were sampled by a commercial data acquisition system (HBM's MGCplus) with a repetition rate of 100 Hz. The test uncertainty of thrust and torque measurement is shown in Table 2. The test uncertainty assessment follows the recommendation of the American Society of Mechanical Engineers [17]. The strut supporting the dynamometer was located sufficiently far away from the rotor plane and measuring planes, *i.e.*, approximately 2.3R. This

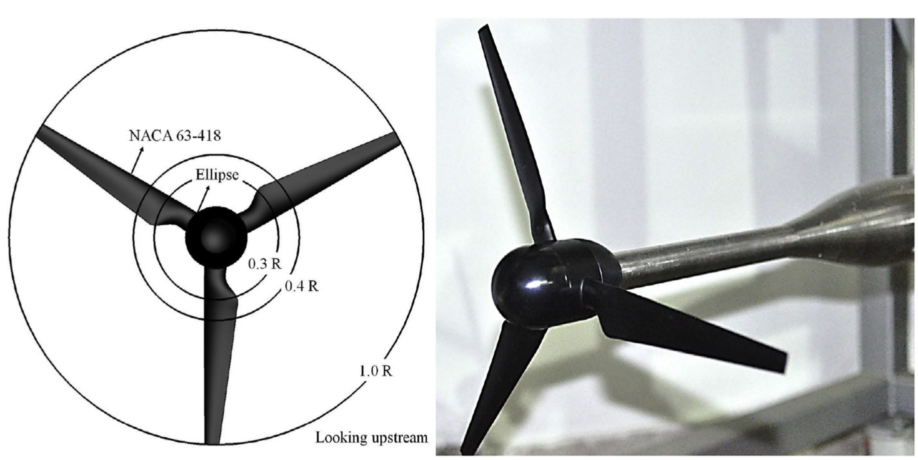

Fig. 1. Design and installation of the test model.