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Marine current energy resource assessment and design of a marine current turbine for Fiji

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ABSTRACT

Pacific Island Countries (PICs) have a huge potential for renewable energy to cater for their energy needs. Marine current energy is a reliable and clean energy source. Many marine current streams are available in Fiji's waters and large amount of marine current energy can be extracted using turbines. Horizontal axis marine current turbine (HAMCT) can be used to extract marine current energy to electrical energy for commercial use. For designing a HAMCT, marine current resource assessment needs to done. A potential site was identified and resource assessment was done for 3 months. The coordinates for the location are 18°12′1.78″S and 177°38′58.21″E; this location is called Gun-barrel passage. The average depth is 17.5 m and the width is nearly 20 m – the distance from land to the location is about 500 m. A multi cell aquadopp current profiler (ADCP) was deployed at the site to record marine currents. Strong marine currents are recorded at this location, as a combination of both tidal and rip currents. The maximum current velocity exceeds 2.5 m/s, for days with large waves. The average velocity was 0.85 m/s and power density for the site was 525 W/m^2. This site has good potential for marine current and HAMCT can be installed to extract power. A turbine with diameter between 5 and 8 m would be suitable for this site. Therefore, a 5 m HAMCT is designed for this location. The HF10XX hydrofoils were used from blade root ($r/R = 0.2$) to tip ($r/R = 1.0$). HF10XX series hydrofoil sections were designed to operate at varying turbine operating conditions; these hydrofoils have good hydrodynamic characteristics at the operating Reynolds number. The turbine is designed to operate at rated marine current speed of 1.5 m/s, cut in speed of 0.5 m/s and cut off speed of 3 m/s at a tip speed ratio (TSR) of 4.2.

1. Introduction

The cost of producing electricity has increased significantly in Pacific Island Countries (PICs) due to increase in fuel price and electricity demand. Burning fossil fuels also causes environmental problems such as global warming. PICs are now looking for alternative energy sources to meet their electricity requirements. Due to limited resources available on land, ocean energy appears a good option; ocean covers more area than land in PICs. One of the reliable and promising ocean energy sources is marine current energy. Many marine current streams are present around Pacific and marine current streams have very high power density.

Near shore, ocean currents are mostly due to tidal current or rip-current, sometimes they can be the combination of both tidal and rip currents. One such marine current stream in Fiji is available at a location called gun-barrel passage. Tidal current is caused by gravitational forces of sun and moon, and centrifugal force of the earth [1]. During flood, tide water moves toward the shore, resulting in tidal current towards the shore, during ebb, tide water recedes from the shore, hence, changing direction of tidal current. This phenomenon can be easily observed at tidal streams where the flow is accelerated naturally. The strength of the tidal current depends on the geometry of the tidal stream and the tidal height difference at the location. The tidal current peaks 4 times for the location where semi-diurnal tides are observed, but the maxima may not be symmetrical for all the locations.

Rip currents originate near surfing zone, and the current direction is seawards, rip currents exceeding 2 m/s are known as mega rip [2]. As the waves break over the breakers, a pressure gradient appears due to difference in wave breaking intensity. The pressure gradient drives along-shore currents towards rip channels from where the water is ejected seawards [3]. Temporary rips always occurs on sand beds, but continuous rips are available at locations where rip channels are in corals or rocks. Although rip currents can be dangerous for surfers and swimmers, they can be a good source of renewable energy if utilized carefully.

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Nomenclature

a	axial flow induction factor
a_0	tangential flow induction factor
A	rotor area (m^2)
c	chord (m)
C_d	drag coefficient (D/½ ρAW^2)
C_l	lift coefficient (L/½ ρAW^2)
C_P	coefficient of pressure $(P_L - P\infty)/(0.5\ \rho AW^2)$
C_{Pw}	power coefficient = $P/(0.5\ \rho AW^2)$
D	drag (N)
g	acceleration due to gravity (m/s^2)
L	lift (N)
P	theoretical power (W)
P_d	power density (kW/m^2)
P_L	local pressure (N/m^2)
P	free-stream static pressure (N/m^2)
P_V	vapor pressure of seawater (N/m^2)
P_{AT}	atmospheric pressure (N/m^2)
r	radius of local blade element (m)
R	blade radius (m)
Re	Reynolds number
t	thickness (m)
T	rotor trust (N)
TSR	tip speed ratio
U_0	free-stream velocity (m/s)
W	relative velocity of rotating blade $\sqrt{U_0^2(1-a)^2 + \Omega^2 r^2 (1+a')^2}$
α	angle of attack for the hydrofoil (degrees)
ρ	density of seawater (kg/m^3)
Ω	rotational speed (rad/s)

Marine current streams have high power density compared to wind energy; therefore small marine current turbine will give similar output to wind turbines with bigger diameter. If the mean peak current exceeds 2 m/s, power can be generated commercially [4]. The energy density (kW/m^2) in a marine stream can be calculated using Eq. (1):

$$P_d = 0.5\ \rho U_0^3 \tag{1}$$

However, all the energy available in the marine stream cannot be extracted. For an isolated turbine, the maximum efficiency is approximately 59%, and it is known as Betz limit [5,6]. The amount of power extracted from channels can even decrease, if the blockage area of channel is reduced. Garrett and Cummins [7] found that the theoretical extractable power from the marine stream could decrease up to 40% if 90% of the stream area is blocked by the turbines.

Several marine current energy converters have been designed and tested over the years, some of which are described by Rourke et al. [8], however, horizontal axis marine current turbine (HAMCT) could be the answer for energy extraction for commercial use. A successful design of HAMCT needs one to understand hydrodynamics of blade and hydrofoils (HAMCT blade sections). The turbine is governed by the hydrodynamic forces resulting from marine currents and rotating blades. The turbine operation is similar to horizontal axis wind turbine (HAWT) [9]; however there are fundamental differences in design and operations that must be taken into account when designing HAMCT rotor. There is difference in Reynolds number, different stall characteristics, required blade strength and occurrence of cavitation.

Hydrofoils must be carefully designed to maximize turbine performance while operating under changing operating conditions and provide enough strength to the blade to avoid structural failure. For numerical analysis of hydrofoil, the 2D panel code Xfoil can be used [10]. Xfoil is a linear vorticity stream function panel method with viscous boundary layer and wake model, and it is suitable for predicting cavitation at initial design stage [11]. Similar to airfoils, hydrofoils must have higher lift over a wide range of α with delayed stall and separation, the L/D ratio should be maximized to maximize turbine output [12]. For cavitation criteria, the minimum C_p should be at good margin to avoid cavitation. The cavitation criteria must be taken into account when designing blade section. Some useful information on cavitation and stall characteristics of marine propellers is presented by Carlton [13] and this information is utilized in designing hydrofoils. In addition, hydrofoils should be thick to provide enough strength to blade.

The rotor performance can be modeled theoretically by blade element momentum (BEM) theory [4]. The BEM theory is based on a combination of momentum and blade element theories. The momentum theory is used to derive the axial and tangential inflow factors, also taking account of tip loss factor. The blade element theory is used to compute the section drag and torque by dividing the rotor blade into number of elemental sections. The combination of both the theories can be used to calculate the rotor thrust loading and power loading by matching the fluid momentum changes to blade forces based on C_l and C_d at the working α of the blade sections. The numerical results computed using BEM theory were validated with experimental results by Bahaj et al. [14], and there was very good agreement between experimental and theoretical results. Therefore, BEM theory can be used to predict theoretical performance of HAMCT rotor.

This paper presents marine current assessment results. The marine current peaks up to 2.5 m/s at times due to large waves. This location has good potential for marine current power generation and is available for more than 14 h every day. In addition, the design of a 5 m diameter, 3-bladed HAMCT rotor that extracts energy from the current, is also presented. Detailed analysis was done for hydrofoils taking into account the cavitation criteria. The chord distribution and twist distribution are optimized to maximize turbine efficiency. The turbine has maximum theoretical efficiency of 47% at rated marine current speed of 1.5 m/s and TSR of 4.2.

2. Marine current resource assessment at gun-barrel passage

Marine current resource assessment was carried out at gun-barrel passage in Fiji, the coordinates of the location are 18°12′1.78″S and 177°38′58.21″E. Very strong marine current was observed at this location. The run-off water from wave breaking combines with tidal current and results in strong current. The tidal current only flows when the water is receding. Fig. 1 shows the details of the gun-barrel passage. The passage is very close to land, about 500 m, which means that turbine installation and power transmission cost will be lower.

Nortek aquadopp current profiler (ADCP) was used to measure the marine current at gun-barrel passage. ADCP measured tidal current at different heights at intervals of 1 m. The current was recorded at intervals of 10 min averaged over 20 s. Apart from velocities, temperature and water level were also recorded. Measurements were performed for 3 months; the location at which ADCP was deployed is also shown Fig. 1. The average depth of the location is around 17.5 m. The marine currents for 3 months