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Design of a horizontal axis tidal current turbine

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HIGHLIGHTS

- A horizontal axis tidal current turbine is designed for a current speed of 2 m/s.
- Five hydrofoils were designed for the blade from the hub to the tip.
- The characteristics of hydrofoils were studied both experimentally and numerically.
- The 3-bladed 10 m diameter rotor has the maximum efficiency of 47.5%.

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ABSTRACT

Pacific Island Countries (PICs) have a huge renewable energy potential to meet their energy needs. Limited resources are available on land; however, large amount of ocean energy is available and can be exploited for power generation. PICs have more sea-area than land-area. Tidal current energy is very predictable and large amount of tidal current energy can be extracted using tidal current energy converters. A 10 m diameter, 3-bladed horizontal axis tidal current turbine (HATCT) is designed in this work. Hydrofoils were designed for different blade location; they are named as HF10XX. The hydrodynamic characteristics of the hydrofoils were analyzed. A thick hydrofoil with a maximum thickness of 24% and a maximum camber of 10% was designed for the root region. The maximum thickness of hydrofoils was varied linearly from the root to the tip for easier surface merging. For the tip region, a thinner hydrofoil of maximum thickness 16% and maximum chamber 10% was designed. It was ensured that the designed hydrofoils do not experience cavitation during the expected operating conditions. The characteristics of the HF10XX hydrofoils were compared with other commonly used hydrofoils. The blade chord and twist distributions were optimized using BEM theory. The theoretical power output and the efficiency of the rotor were also obtained. The maximum power at the rated current of 2 m/s is 150 kW and the maximum efficiency is 47.5%. The designed rotor is found to have good efficiency at current speeds of 1–3 m/s. This rotor has better performance than some other rotors designed for HATCT.

1. Introduction

Concerns about the rise in fuel prices and continuous increase in carbon emissions have forced researchers to explore alternative sources of energy [1]. In pacific island countries, imported fossil fuel or petroleum is the primary source for the commercial energy needs. Most isolated islands in pacific use petroleum for transportation and electricity needs. Renewable energy resources are abundant in pacific island countries, and offer a good alternative energy source. The ocean offers a large energy source, for example wave energy, ocean thermal energy, and tidal energy that are yet to be significantly tapped. Tidal current energy is vast, reliable, regular and the most predictable renewable energy resource [2]. Various global studies have shown that tidal current energy has large potential as a predictable sustainable resource for commercial scale generation of electrical power. Tidal current energy is much easier and cheaper to extract using tidal current converters, with less harmful effects to the environmental compared to tidal barrages [3]. Many tidal current energy extraction devices have been developed, but HATCT is the most developed one; it can be used to extract a large amount of tidal current energy from tidal streams. The design and operation of HATCT are similar to those of a Horizontal axis wind turbine (HAWT) [4]. Many developments have taken place in field of HATCT during the recent years, moving from model testing to prototype development and installation. Batten et al. [5,6] made good contribution to the field by designing and model testing of bi-directional marine current turbines. Lee et al. [7] developed a CFD method for power prediction of HATCT. Hwang et al. [8] designed bi-directional horizontal axis tidal turbine (HATT) with improved efficiency by implementing individual blade control. Many turbine with nozzle/duct were developed to

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Nomenclature

a	axial flow induction factor
a_0	tangential flow induction factor
A	rotor area (m^2)
b	span of hydrofoil in the wind tunnel test section (m)
c	chord (m)
C_D	drag coefficient ($D/0.5\rho bcW^2$)
C_L	lift coefficient ($L/0.5\rho bcW^2$)
C_P	coefficient of pressure ($(P_L - P_\infty)/(0.5\rho bcW^2)$)
C_{Pw}	power coefficient = $P/(0.5\rho AW^2)$
D	drag (N)
g	acceleration due to gravity (m/s^2)
h	local head of water at the blade tip immersion $h = h_t + R - r$ (m)
h_t	tip immersion depth (m)
k	Goldstein factor
K_1	wind-tunnel correction constant for solid blockage effects (0.74)
L	lift (N)
M_v	model volume (m^3)
N	number of blades
P	rotor power (W)
P_L	local pressure (N/m^2)
P_∞	freestream static pressure (N/m^2)
P_V	vapor pressure of sea water (N/m^2)
P_{AT}	atmospheric pressure (N/m^2)
Q	rotor tangential force (N)
r	radius of local blade element (m)
R	blade radius (m)
t	thickness (m)
T	rotor thrust (N)
U_0	free-stream velocity (m/s)
V_u	uncorrected free-stream velocity (m/s)
W	relative velocity (m/s) of rotating blade $\sqrt{U_o^2(1-a)^2 + \Omega^2 r^2 (1+a')^2}$
X_r	radial distance (r/R)
x	axial coordinate
y	transverse coordinates (m)
α	angle of attack (°)
ρ	density of sea water (kg/ m^3)
ε^{sb}	solid blockage correction factor
Ω	rotational speed (rad/s)
ϕ	angle between W and the plane of rotation (°)
φ	blade pitch angle (°)
σ	cavitation number
σ_k	solidity ratio (cN/2R)

Abbreviation

HATCT	horizontal axis tidal current turbines
HAWT	horizontal axis wind turbine
Re	Reynolds number
TKE	turbulence kinetic energy
TSR	tip speed ratio
BEM	blade element momentum
CFD	computational fluid dynamics

improve turbine efficiency – for example the RTT by Lunar Energy [9], SeaGen by Marine Current Turbines (MCTs) [10], some early investigations and testing performed by Thorpe [11] and Clean Current's tidal turbine [12]. However, adding nozzle/duct will increase manufacturing cost as well as weight, the additional manufacturing cost and weight must be justified in terms of increased efficiency. Sale et al. [13] did optimization of HATCT blades using genetic algorithm, which is found to be an effective method for optimizing turbine blades with improved hydrodynamic performance.

For commercial viability of HATCT, a peak tidal current velocity of over 2 m/s is required [5]; a lot of research is being done on HATCT designs, so it can have high efficiency even at lower tidal current velocities. Development and progress in HATCT have made it possible to extract tidal current energy from bi-directional tidal streams by pitching the turbine blade to 180° when the flow reverses [14]. Hydrofoils are individual blade elements that help to convert flow energy into mechanical energy by generating a force and their better design contributes to improved overall performance of the blade. Lift force produced by the hydrofoil rotates the blade as a component of this lift gives the blade its rotating torque. Successful design of blades for HATCT requires one to study the hydrodynamic characteristics of hydrofoils. Hydrofoils work in a similar way as airfoils; however, there are a number of fundamental differences in the design and operation of hydrofoils, which require further investigation, research and development. Particular differences are changes in Reynolds number (Re), different stall characteristics and the possible occurrence of cavitation on hydrofoils. Some useful information is available on the cavitation and stall characteristics of marine propellers (e.g. Ref. [15]), which are very useful for designing of hydrofoils.

Once the cavitation inception is predicted, then the blade element momentum theory (BEM theory) can be applied for predicting the performance of HATCT [13]. BEM theory is widely used for predicting the performance of marine current turbines and the spanwise distribution of blade loading [6]. Another factor that must be taken into account when designing hydrofoils is that water is approximately 830 times denser than air, therefore water exerts larger amount of thrust on marine turbine blades [16]. Thus there is a need to design thicker hydrofoils to meet the strength requirement of the blade to withstand large thrust forces. The designed hydrofoils must have good hydrodynamic characteristics for better performance and delayed cavitation inception.

In the present work, hydrofoils were designed for different sections of a HATCT blade. These sections are for a 3-bladed, 10 m diameter rotor, with an operational tip speed ratio (TSR) of 4 and a free-stream velocity of 2 m/s. The objective was to achieve good hydrodynamic characteristics at tidal current velocities of 1–3 m/s. These hydrofoils were designed to meet certain turbine requirements that are; high performance, good blade strength and non-occurrence of cavitation. All hydrofoils that are designed meet the major requirements of high C_L and high L/D ratio over a wide range of angles of attack. The sections are thick enough to provide strength to the blade and the hydrofoils do not encounter the problem of cavitation at operational TSR of 4 and free-stream velocities up to 3 m/s. Numerical and experimental studies were performed on the HF1020 blade at a location of 60% of the blade from the center of the hub. Initial results were obtained with Xfoil and were verified with both experimental and CFD results.

2. Turbine design parameters and operating conditions

The behavior of hydrofoils is different on a rotating blade compared to when it is not rotating. Once the rotor is in motion, the blade section starts to experience a relative component of tidal current velocity at various angles of attack (α) depending on the blade parameters. The lift and drag forces acting on the hydrofoils