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Experimental and numerical studies of blade roughness and fouling on marine current turbine performance

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ABSTRACT

The impact of blade roughness and biofouling on the performance of a two-bladed horizontal axis marine current turbine was investigated experimentally and numerically. A 0.8 m diameter rotor (1/25th scale) with a NACA 63-618 cross section was tested in a towing tank. The torque, thrust and rotational speed were measured in the range $5 < \lambda < 11$ (λ = tip speed ratio). Three different cases were tested: clean blades, artificially fouled blades and roughened blades. The performance of the turbine was predicted using blade element momentum theory and validated using the experimental results. The lift and drag curves necessary for the numerical model were obtained by testing a 2D NACA 63-618 aerofoil in a wind tunnel under clean and roughened conditions. The numerical model predicts the trends that were observed in the experimental data for roughened blades. The artificially fouled blades did not adversely affect turbine performance, as the vast majority of the fouling sheared off. The remaining material improved the performance by delaying stall to higher angles of attack and allowing measurements at lower λ than were attainable using the clean blades. The turbine performance was adversely affected in the case of roughened blades, with the power coefficient (C_P) versus λ curve significantly offset below that for the clean case. The maximum C_P for this condition was 0.34, compared to 0.42 for the clean condition.

1. Introduction

Marine current power is an emerging renewable technology and although technology can be transferred from wind turbines, there is a need for research specific to marine current turbines. Ng et al. [1] provide a comprehensive review of the past decade of horizontal axis marine current turbine research. Recent experimental studies on marine current turbine performance include [2–4]. Horizontal axis marine current turbines are typically modelled using blade element momentum (BEM) theory adapted from wind turbines [5–7]. BEM theory can be used to predict turbine performance in terms of the power and thrust coefficients, as well as the spanwise blade loadings. Two potential performance issues for marine current turbines are the roughening of the turbine blades due to impact, cavitation or scour due to particulates, and the fouling of the turbine blades by marine growth. This issue was identified by Fraenkel [8] and Ng et al. [1] who also point out the need for high reliability given the difficult maintenance access issues in the underwater environment.

Significant losses in power output and changes to the stall behaviour have been reported for wind turbines due to the accumulation of insects and contaminants along the leading edge of the turbine blades [9]. New aerofoil families were designed specifically for wind turbine applications with the aim of reducing the effects of leading edge roughness [10]. Roughness, particularly on the leading edge, reduces the maximum lift coefficient and increases the minimum drag coefficient [10–13]. The effect of leading edge roughness increases with aerofoil thickness, which is an issue for wind and tidal applications as thick aerofoils are needed near the blade root to withstand the high forces [10,11]. Timmer and Schaffarczyk [11] investigated the effect of leading edge roughness on thick aerofoils for wind turbine applications. The lift coefficient was reduced by 32–45% depending on *Re* for a DU 97 type aerofoil with carborundum 60 (grain size of 0.25 mm) wrapped around the leading 40 mm (8% of *c*). Other researchers found that the application of leading edge grit roughness to S809 [12] and NACA 4415

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[13] aerofoils at $Re_c = 1 \times 10^6$ reduced the maximum C_L by 16% in both cases and increased the minimum C_D by 41% and 67%, respectively.

There have been few studies to investigate the effects of roughness or fouling on marine current turbines. Orme et al. [14] investigated the potential effects of barnacles. The lift and drag coefficients for an aerofoil covered with idealised barnacles of different sizes and distribution densities were determined using a wind tunnel. The lift to drag ratio decreased with both increasing barnacle size and distribution density. It was concluded that the presence of barnacles would have a detrimental effect on turbine efficiency, and that further studies on fouling on marine current turbines are warranted. Batten et al. [6] investigated the potential effects of an increase in blade roughness or blade fouling using a numerical model. They assumed that the presence of roughness or fouling would increase the drag coefficient, C_D, by up to 50%. The lift coefficient was not altered in their study. The model predicted a decrease in power coefficient, C_P, of 6–8% at $\lambda > 4$, where λ is the tip speed ratio.

There are few full-scale horizontal axis marine current turbines in operation at the present time. An informal survey of operators found that most turbine blades are treated with an antifouling coating and most operators reported little to no fouling accumulation on turbine blades. Polagye and Thomson [15] conducted a study on the performance of materials commonly used in marine current turbines. Coupons of various materials were deployed in a region with a tidal current in the order of 3 m/s. Materials that could be used in a rotor, including carbon fibre and antifouling coatings, accumulated very little to no fouling during the study period. However, this information does not discount the potential for deterioration or fouling of the blade surfaces over longer periods of time.

This paper presents experimental and numerical data for a model-scale 2-bladed horizontal axis marine current turbine. The turbine was tested in a towing tank in the clean, artificially fouled and roughened condition to obtain nondimensional coefficients of power and thrust versus tip speed ratio. Separately, the NACA 63-618 aerofoil section used for the turbine blades was tested in a wind tunnel to obtain the lift and drag curves in both clean and roughened conditions. These aerofoil performance curves were input into an in-house numerical model based on the blade element momentum theory. The experimentally validated numerical model was able to accurately predict the performance of the turbine in the clean condition and provides new data on turbine performance under roughened conditions. This is a valuable tool for both turbine designers and operators.

The nomenclature used throughout this paper is defined in Table 1. The performance of the marine current turbine is presented in terms of three key parameters: the power coefficient, C_P, thrust coefficient, C_T, and tip speed ratio, λ:

$$C_P = P/\left(\frac{1}{2}\rho U^3 \pi R^2\right) \tag{1}$$

$$C_T = T/\left(\frac{1}{2}\rho U^2 \pi R^2\right) \tag{2}$$

$$\lambda = \Omega R/U \tag{3}$$

2. Experiment details

2.1. Physical turbine model

The marine current turbine model consisted of a two-bladed rotor with a diameter of $d = 0.8$ m. This is 1/25th scale of operational turbines such as SeaGen [16]. The turbine was based on the U.S. National Renewable Energy Laboratory (NREL) design. The rotor blades have a NACA 63-618 cross section. This aerofoil was selected as the lift coefficient is Reynolds number independent in the operating range based on data from Miley [17] and XFoil predictions [18]. The Reynolds number at 70% span based on the relative velocity and chord length is approximately $Re_c = 4 \times 10^5$. The blades have a 13° twist and 62% taper. The blade geometry is detailed in Table 2. The blades are constructed of 6061 aluminium and were anodised for corrosion resistance. The blades are fixed to a hub with a fairwater end cap, as shown in Fig. 1.

Real biofilms were not able to be grown on a rotating turbine or be tested in the towing tank. Thus the effect of marine biofouling

Table 1
Nomenclature.

A_{ts}	Cross-sectional area of test section (m^2)	c	Blade chord (m)
B	Number of blades	d	Diameter (m)
C_D	Drag coefficient	d_{cyl}	Diameter of blades at root (m)
C_L	Lift coefficient	g	Gravitational acceleration (9.81 m/s^2)
C_M	Pitching moment coefficient	h_{ts}	Height of test section (m)
C_P	Power coefficient	p	Pressure (Pa)
C_T	Thrust coefficient	q	Dynamic pressure (Pa)
D	Drag force (N)	r	Local radius (m)
F	Tip loss correction factor	Δr	Length of blade with cylindrical c/s (m)
K_1	Wind tunnel blockage correction factor	s	Blade span (m)
L	Lift force (N)	t	Aerofoil thickness (m)
M	Pitching moment (Nm)	w_{ts}	Width of test section (m)
P	Power (W)	α	Angle of attack (o)
Q	Torque (N.m)	δ	Boundary layer thickness (m)
R	Blade radius (m)	φ	Angle of relative wind (o)
R_a	Mean roughness height (μm)	σ'	Local solidity ratio
R_h	Hub radius (m)	σ_{sc}	Correction factor for streamline curvature
R_{ku}	Kurtosis of roughness sample	τ_{wall}	Wall shear stress (Pa)
R_q	Root mean square roughness height (μm)	λ	Tip speed ratio
R_{sk}	Skewness of roughness sample	λ_r	Local tip speed ratio
R_z	Average max height of roughness (μm)	θ_p	Section pitch angle (o)
Re_c	Reynolds number based on chord	ρ	Fluid density (kg/m^3)
Re_x	Reynolds number based on distance	Ω	Rotational velocity (rad/s)
T	Thrust force (N)	*Subscript*	
U	Freestream velocity (m/s)	u	Uncorrected data
U_{rel}	Relative velocity (m/s)	w	Wake
a	Axial induction factor	∞	Freestream
a'	Angular induction factor		

Table 2
Blade geometry.

r/R	c/R	Twist (deg)	t/c (%)
0.263	0.170	12.9	25.4
0.300	0.165	11.5	21.0
0.338	0.160	10.2	18.5
0.385	0.153	8.7	18.0
0.445	0.145	7.4	18.0
0.535	0.132	6.0	18.0
0.625	0.119	5.1	18.0
0.685	0.110	4.5	18.0
0.745	0.101	4.0	18.0
0.805	0.092	3.6	18.0
0.865	0.082	3.1	18.0
0.925	0.073	2.7	18.0
1.000	0.060	2.1	18.0