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

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A B S T R A C T

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 $5 < \lambda < 11$ ($\lambda$ = 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 $\lambda$ 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 $\lambda$ 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 carboumdum 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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aerofoils at $Re = 1 \times 10^6$ 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 change 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 $\lambda$ 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 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 change 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 $\lambda$ is the tip speed ratio.

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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, $\lambda$:

$$C_p = \frac{P}{\frac{1}{2} \rho U^2 \pi R^2}$$  (1)

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

$$\lambda = \Omega R / U$$  (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 $Re_c = 4 \times 10^6$. 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>
<thead>
<tr>
<th>Table 1</th>
<th>Nomenclature.</th>
</tr>
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<tbody>
<tr>
<td>$A_n$</td>
<td>Cross-sectional area of test section (m²)</td>
</tr>
<tr>
<td>$B$</td>
<td>Number of blades</td>
</tr>
<tr>
<td>$C_{D0}$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$C_l$</td>
<td>Lift coefficient</td>
</tr>
<tr>
<td>$C_{M0}$</td>
<td>Pitching moment coefficient</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Power coefficient</td>
</tr>
<tr>
<td>$C_T$</td>
<td>Thrust coefficient</td>
</tr>
<tr>
<td>$D$</td>
<td>Drag force (N)</td>
</tr>
<tr>
<td>$F$</td>
<td>Tip loss correction factor</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Wind tunnel blockage correction factor</td>
</tr>
<tr>
<td>$L$</td>
<td>Lift force (N)</td>
</tr>
<tr>
<td>$M$</td>
<td>Pitching moment (Nm)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Torque (Nm)</td>
</tr>
<tr>
<td>$R$</td>
<td>Blade radius (m)</td>
</tr>
<tr>
<td>$R_m$</td>
<td>Mean roughness height (μm)</td>
</tr>
<tr>
<td>$R_n$</td>
<td>Hub radius (m)</td>
</tr>
<tr>
<td>$R_u$</td>
<td>Kurtosis of roughness sample</td>
</tr>
<tr>
<td>$R_{avg}$</td>
<td>Root mean square roughness height (μm)</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Skewness of roughness sample</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Reynolds number based on chord</td>
</tr>
<tr>
<td>$R_{Re}$</td>
<td>Reynolds number based on distance</td>
</tr>
<tr>
<td>$T$</td>
<td>Thrust force (N)</td>
</tr>
<tr>
<td>$U$</td>
<td>Freestream velocity (m/s)</td>
</tr>
<tr>
<td>$U_{rel}$</td>
<td>Relative velocity (m/s)</td>
</tr>
<tr>
<td>$a$</td>
<td>Axial induction factor</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of attack (°)</td>
</tr>
<tr>
<td>$\alpha'$</td>
<td>Angular induction factor</td>
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</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Blade geometry.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r/R$</td>
<td>$c/R$</td>
</tr>
<tr>
<td>0.263</td>
<td>0.170</td>
</tr>
<tr>
<td>0.300</td>
<td>0.165</td>
</tr>
<tr>
<td>0.338</td>
<td>0.160</td>
</tr>
<tr>
<td>0.385</td>
<td>0.153</td>
</tr>
<tr>
<td>0.445</td>
<td>0.145</td>
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<tr>
<td>0.535</td>
<td>0.132</td>
</tr>
<tr>
<td>0.625</td>
<td>0.119</td>
</tr>
<tr>
<td>0.685</td>
<td>0.110</td>
</tr>
<tr>
<td>0.745</td>
<td>0.101</td>
</tr>
<tr>
<td>0.805</td>
<td>0.092</td>
</tr>
<tr>
<td>0.865</td>
<td>0.082</td>
</tr>
<tr>
<td>0.925</td>
<td>0.073</td>
</tr>
<tr>
<td>1.000</td>
<td>0.060</td>
</tr>
</tbody>
</table>
was approximated using readily available materials. Three different cases were tested: (A) baseline case with clean blades, (B) blades fouled with a 1.1 mm thick layer of lithium grease impregnated with diatomaceous earth as an approximation of slime growth (Fig. 2a), and (C) blades roughened with a thin layer of randomly applied contact cement to model increased blade roughness or growth by hard deposits such as barnacles or encrusting bryozoans (Fig. 2b).

2.2. Towing tank testing

The model turbine was tested in the large towing tank at the United States Naval Academy. The towing tank is 116 m long, 7.9 m wide and 4.9 m deep. The torque and thrust were measured using a Cussons Technology R46-01 dynamometer, installed directly behind the hub (Figs. 1 and 3). The dynamometer was connected to a 90° gear box. The rotational speed of the shaft and the position of the reference blade were measured using a BEI Sensors encoder model HS35. The speed of the shaft was controlled using a differential electromagnetic brake (Placid Industries Hysteresis Brake model H250). The turbine was attached to the towing carriage via a streamlined strut that resulted in a hub depth of 2.25 \(d\) (1.8 m), as shown in Fig. 3.

The turbine was towed at a constant speed of \(U = 1.68 \text{ m/s}\). This speed was selected to maximise the Reynolds number whilst staying within the torque and thrust limits of the dynamometer. The towing speed, shaft rotational speed, brake voltage, torque and thrust were acquired simultaneously using a data acquisition system at 700 Hz. The torque, thrust and rotational speed were measured at a range of tip speed ratios in the range \(5 < \lambda < 11\).

The towing tank data were corrected for blockage using the actuator disk methodology [2]. Turbine wake expansion is blocked by the sides of the towing tank accelerating the flow as compared to the unblocked case resulting in artificially high measured values. Correction factors for each of the performance parameters (\(\lambda, C_P, C_T\)) are calculated using the inflow speed, in this case the carriage speed of \(U = 1.68 \text{ m/s}\), and the measured thrust coefficient, \(C_T\). The average blockage correction factors were 0.99, 0.97 and 0.98 for \(\lambda, C_P\) and \(C_T\), respectively.

An uncertainty analysis was performed using the Taylor series method described by Coleman and Steele [19]. The precision and bias estimates for each measured variable were determined and then propagated to determine the uncertainty in the calculated variables at a confidence of 95%. The estimates of precision were determined from four repeated runs at the point of maximum efficiency, \(\lambda \sim 6\). The bias errors, with the exception of errors associated with the calibration of the instrumentation, were eliminated.
during the re-zeroing process which was undertaken prior to every single measurement run. During the re-zero, the system recorded the voltage readings at 700 Hz from each of the sensors. At the end of the re-zero period (30 s), the average voltage value was calculated for that period. This value (the bias) was removed from each of the measured quantities at every sample, prior to conversion to output readings. The calibration error was taken from the calibration cards for each piece of measurement equipment, all of which were tested and re-calibrated prior to the experiment. The overall uncertainties, quoted at 95% confidence, for \( \lambda \), \( C_D \) and \( C_T \) were \( \pm 1.0\% \), \( \pm 1.3\% \) and \( \pm 1.2\% \), respectively.

### 2.3. Wind tunnel testing

To produce accurate results from the blade element momentum theory in-house numerical model, the lift and drag coefficient curves in terms of angle of attack for the NACA 63-618 aerofoil were required at the operational Reynolds number of approximately \( Re_a = 4 \times 10^5 \). This Reynolds number is significantly lower than any of the published data for the NACA 63-618 aerofoil, e.g. Ref. [17]. The lift coefficient, \( C_L \), and drag coefficient, \( C_D \), are defined in equations (4) and (5), respectively.

\[
C_L = \frac{L}{\frac{1}{2} \rho U^2 cs} \quad \text{(4)}
\]

\[
C_D = \frac{D}{\frac{1}{2} \rho U^2 cs} \quad \text{(5)}
\]

A two-dimensional NACA 63-618 aerofoil with a chord of 0.23 m, a span of 0.79 m and an aspect ratio of 3.4 was tested in an Eiffel wind tunnel at the United States Naval Academy (Fig. 4) in both the clean and roughened condition. Roughness was added to the aerofoil by randomly applying contact cement with a paint brush and allowing it to dry. Four cases were tested as shown in Fig. 5: (1) clean aerofoil, (2) leading edge lightly roughened (10% of chord), (3) whole aerofoil lightly roughened, and (4) whole aerofoil heavily roughened.

The subsonic tunnel at the United States Naval Academy is a low-turbulence, open-return, closed-jet facility with a test section measuring 1.12 m \( \times \) 0.79 m \( \times \) 3.05 m. The tunnel is driven by a 185 kW motor controlled by a variable frequency drive and delivers a maximum velocity of approximately 100 m/s. Flow management devices include a high-aspect-ratio honeycomb flow straightener and a series of fine mesh screens. The three dimensional contraction has a ratio of 9.6:1, resulting in a freestream turbulence intensity of 0.06%. The wind tunnel dynamic pressure was determined by measuring the contraction pressure using a Honeywell SCX series differential pressure transducer and using the contraction ratio. The aerofoil was mounted to an AEROLAB six component pyramidal force balance, which was used to measure the lift force. The gap between the tip of the 2D aerofoil and the tunnel roof was 3 mm. The angle of attack was controlled by computer-driven stepper motors and had a range of \( \pm 30^\circ \).

The drag force was obtained by measuring the wake profile with a wake rake and using the momentum method [20,21], as the force balance was not sensitive enough to accurately measure the small drag forces. The momentum and continuity equations were applied to a control volume as shown in Fig. 6, assuming two-dimensional flow. The drag on the aerofoil is given by equation (6). Equation (6) was manipulated using the Bernoulli equation to give equation (7), which was used in the analysis.

\[
D = \rho \frac{d}{h_s} \int \left( U_w U_w - U_w^2 \right) dy \quad \text{(6)}
\]

\[
D = 2 \rho \frac{d}{h_s} \int \left( \sqrt{p_w - p_s} \sqrt{p_w - p_s} - (p_w - p_s) \right) dy \quad \text{(7)}
\]

The wake rake (Fig. 4) consisted of 11 Pitot tubes, spaced 12.7 mm apart. To obtain a finer resolution, the rake was rotated at an angle of 76.7°, giving a spacing of 2.9 mm. The rotated rake was located 400 mm downstream of the aerofoil (approximately 1.75 chord lengths). It was traversed in the spanwise direction to capture both the freestream pressure and the pressure in the wake. A Pitot-static tube, located in the same plane as the rake, was used to measure both the freestream total pressure and the static pressure. The pressures were measured using an AEROLAB pressure transducer array with an accuracy of 0.002% of the full scale reading. The lift, wake profile and tunnel dynamic pressure were obtained for increasing angles of attack, starting from \( \alpha = -7^\circ \) and extending out to \( \alpha \sim 10^\circ \) for the wake profiles and \( \alpha \sim 25^\circ \) for the lift force. The tunnel dynamic pressure was monitored and changed as necessary to maintain a constant \( Re \) during each test.

The wind tunnel data were corrected for blockage and streamline curvature according to the methods outlined in Barlow et al. [20] and Selig and McGranahan [21]. The model reduces the cross-sectional area of the test section, an effect known as solid blockage. This causes the local velocity to increase, hence increasing the aerodynamic forces for a given angle of attack. Due to the closed nature of the wind tunnel, the wake velocity is lower than the velocity outside of the wake which must speed up to maintain continuity. This causes a pressure gradient on the model, a phenomenon known as wake blockage. The data were corrected for the effects of solid and wake blockage using equations (8) and (9), respectively. The presence of the wind tunnel side walls alters the normal curvature of the streamlines that occur around a lifting aerofoil, effectively increasing the camber of the aerofoil. This streamline curvature affects the lift, moment about the quarter-chord and the angle of attack by way of the streamwise curvature factor, given in equation (10).

\[
\epsilon_{sb} = K_1 (\text{model volume})/A_{ts}^{3/2} \quad \text{(8)}
\]

\[
\epsilon_{wb} = (c/2 \omega_{ts}) C_{D,u} \quad \text{(9)}
\]

\[
\sigma_{sc} = \pi^2 c^2 / 48 h_{ts}^2 \quad \text{(10)}
\]

The overall corrections to the various quantities for blockage and streamline curvature are combined as given below.
\( V = V_u(1 + \varepsilon_{sb} + \varepsilon_{wb}) \) \tag{11}

\( Re = Re_u(1 + \varepsilon_{sb} + \varepsilon_{wb}) \) \tag{12}

\( \alpha = \alpha_u + 57.3\sigma_{sc}/2\pi(C_L u + 4C_{M1u}) \) \tag{13}

\( C_L = C_{Lu} (1 - \sigma_{sc} - 2(\varepsilon_{sb} + \varepsilon_{wb})) \) \tag{14}

\( C_D = C_{Du} (1 - 3\varepsilon_{sb} - 2\varepsilon_{wb}) \) \tag{15}

\( C_{M_2} = C_{M2u} (1 - 2(\varepsilon_{sb} + \varepsilon_{wb})) + \sigma_{sc}C_L/4 \) \tag{16}

The uncertainty analysis on the wind tunnel data was conducted using the Taylor series method described by Coleman and Steele [19]. The precision and bias estimates for each measured variable were determined and then propagated to determine the uncertainty in the calculated variables at a confidence of 95%. The uncertainties in the measured variables for \( \alpha = 7^\circ \) at \( Re_c = 4 \times 10^5 \) were 1.6% in \( U \), 2.7% in \( L \), 6.6% in \( D \) and 0.1° in \( \alpha \). The uncertainties in the calculated variables were 4.3% and 7.5% for \( C_L \) and \( C_D \), respectively.

2.4. Roughness characterisation

The roughness of the applied contact cement on the marine current turbine blades and the 2D aerofoil was characterised by simultaneously roughening small aluminium coupons with the contact cement. The coupons were then sputtered with a thin film of gold. A non-contact optical profiler (Wyko NT9100) was used to obtain three-dimensional topographical maps of 14 mm × 11 mm sections of the sputtered coupons. These large sample areas were obtained by stitching together 64 scans of the surface topography. The system uses vertical scanning interferometry to measure the surface profile. The profiler accurately measures roughness up to 2 mm in height with a vertical resolution of 3 nm. The data were filtered to remove tilt and noise using the tilt removal function and a digital low pass filter.

3. Numerical model

Blade element momentum (BEM) theory [7], which was originally developed for wind turbines, was used to model the performance of the marine current turbine for various blade conditions. BEM theory is a combination of momentum theory and blade element theory. The basic theory will be outlined here. For a detailed treatment of the theory, please refer to Manwell et al. [7]. The nomenclature used is defined in Table 1.

Momentum theory employs a control volume analysis of the forces on the blades using conservation of linear and angular momentum to determine equations for differential thrust (equation (17)) and torque (equation (18)), based on the axial and angular induction factors, \( a \) and \( a' \).

\[
\text{d}T = F_p U^2 \alpha (1 - a) \pi \text{dr} \tag{17}
\]

\[
\text{d}Q = 4F_a' (1 - a') \rho U \pi r^2 \text{Q} \text{dr} \tag{18}
\]

Blade element theory is the analysis of the forces on the blade in terms of the lift and drag coefficients of the aerofoil. As the aerofoils...
for a turbine are twisted and tapered and may also have a changing aerofoil section, each blade is divided up into sections. The resulting expressions for the differential normal force (thrust) and differential torque are given in equations (19) and (20), respectively.

\[
dF_N = dT = 2 \rho U_{rel}^2 (C_L \cos \phi + C_D \sin \phi) cd\theta
\]

\[
dQ = B \rho U_{rel}^2 (C_L \sin \phi - C_D \cos \phi) cd\theta
\]

The thrust and torque equations from momentum theory (equations (17) and (18)) and blade element theory (equations (19) and (20)) are equated in blade element momentum theory to determine equations for the induction factors \( \alpha \) and \( \omega \). In calculating \( \alpha \) and \( \omega \) it has been assumed that \( C_D = 0 \), which is a reasonable assumption for \(-7 < \alpha < 10\), as shown in Fig. 8b. The local solidity ratio is defined in equation (23).

\[
a = 1/(1 + 4F \sin^2 \phi/(\sigma' C_L \cos \phi))
\]

\[
a' = 1/(4F \cos \phi/(\sigma' C_L) - 1)
\]

\[
\sigma' = Bc/2\pi r
\]

The BEM model requires several inputs: the lift and drag coefficients and the geometry of the turbine blade aerofoil, the number of blades and the required tip speed ratio. The lift and drag coefficients under smooth and roughened conditions were determined experimentally as described above.

The flow conditions and forces at each blade section were determined numerically by solving for \( C_L \) and \( \alpha \) at each blade section. The lift coefficient can be expressed in terms of the local tip speed ratio, local solidity ratio and the relative wind angle as given in equation (24). Since \( \alpha = \theta + \alpha \), \( C_L \) can be plotted in terms of the angle of attack, \( \theta \). The intersection of this curve at each blade section with the experimental lift curve defines \( C_L \) and \( \alpha \) for that blade section. Once \( \alpha \) is known the angular and axial induction factors and hence power and thrust coefficients can be calculated at each blade section. The differential power and thrust coefficients are given in equations (25) and (26). They can be integrated to determine the overall power and thrust coefficients for a given tip speed ratio.

\[
C_L = 4F \sin \phi(\cos \phi - \lambda_\theta \sin \phi) / \sigma' (\sin \phi + \lambda_\theta \cos \phi)
\]

\[
dC/P/\lambda_\theta = \left(8/\lambda^2\right) \left(F \lambda^2 a'(1-a)/(1-(C_D/C_L)\cot \phi)\right)
\]

\[
dC/\alpha = \left(2/R^2\right) \sigma' (1-a)^2(C_L \cos \phi + C_D \sin \phi)/\sin^2 \phi
\]

Tip loss was accounted for using a tip loss correction factor, as given in equation (27). The thrust coefficient was modified to include the thrust on the hub and the root of the blades. The thrust on the hub was modelled as the drag on a semisphere, with \( C_{D,\text{hub}} = 0.42 \), as given in equation (28). The thrust on the root was modelled as the drag on a cylinder, as given in equation (29). The drag coefficient of the 0.032 m diameter cylinder was taken as \( C_{D,\text{root}} = 1.7 \), based on the Reynolds number at the blade root.

\[
F = (1/90)\cos^3 \theta [\exp(-B/2)(1-r/R)/(r/R)] \sin \phi]
\]

\[
C_{T,\text{hub}} = C_{D,\text{hub}} R^2 / R^2
\]

\[
C_{T,\text{root}} = C_{D,\text{root}} \Delta \tau \text{cyl} \left(1 + \lambda_\theta^2\right) B / (\pi R^2)
\]

4. Results and discussion

4.1. Roughness

The roughness statistics of the contact cement applied to the turbine blade and the 2D aerofoil are given in Table 3. These statistics represent the entire 14 mm \(\times\) 11 mm surface of each sample. The roughness parameters are defined in Table 1. \( R_u \), \( R_a \) and \( R_d \) provide information about the roughness height of each surface. The skewness and kurtosis, \( R_{sk} \) and \( R_{ku} \), provide information about the surface texture. Skewness measures the asymmetry of the surface about the mean plane and kurtosis measures the range of roughness scales. The relative roughness of the samples has been calculated as the ratio of the average maximum roughness height, \( R_z \), to the chord length, \( c \). The surface topography of each sample is given in Fig. 7. The roughnesses on the 2D aerofoil had similar root mean square roughness heights \( R_a \), but very different average maximum roughness heights \( R_u \), skewness \( R_{sk} \) and kurtosis values \( R_{ku} \). The heavy roughness case on the 2D aerofoil had a high proportion of the surface falling within a narrow height band, evidenced by the high kurtosis value. The light roughness on the 2D aerofoil and the roughness on the turbine blade had far lower kurtosis values, which indicate that these surfaces were more random. The contact cement applied to the turbine blade was the roughest in terms of both the roughness height parameters and the relative roughness.

4.2. Lift and drag curves for 2D NACA 63-618

The smooth aerofoil lift and drag coefficients determined from the wind tunnel testing are compared to the data from Miley [17] and XFOil [18] in Fig. 8. The lift coefficient, \( C_L \), was Reynolds number independent at the conditions tested. The experimental data collapse and compare well to the data from Miley [17] and XFOil [18], as shown in Fig. 8a. The drag coefficient, \( C_D \), was Reynolds number independent for \( Re_c = 5 \times 10^5 \). The experimental data at \( Re_c = 5 \times 10^5 \) and \( 1 \times 10^6 \) collapse and agree with Miley [17] and XFOil [18] for similar \( Re_c \). This result is significant, given that the model marine current turbine operates at approximately \( Re_c = 4 \times 10^5 \) (at 70% span), which is in the Reynolds number dependent range.

The three roughened aerofoil cases are compared to the smooth aerofoil case and Miley data [17] in Fig. 9. The effect of roughness was to decrease the maximum lift coefficient by an average of 11% for all roughness cases. The roughness also increased the stall angle from \( \alpha = 10^\circ \) for the smooth aerofoil to \( \alpha = 16^\circ \) for the roughened aerofoils. The results show that roughness on the leading edge has a significant effect on the lift, as the case with the entire blade roughened had only slightly reduced lift and slightly increased drag over the leading edge roughness case, as shown in Figs. 9 and 10. The drag coefficient increased with increasing roughness. The minimum drag coefficient at \( Re_c = 5 \times 10^5 \) increased 49%, 59% and 153% for the leading edge, light entire blade roughness and heavy entire blade roughness, respectively.

<table>
<thead>
<tr>
<th>Case</th>
<th>( R_u (\mu m) )</th>
<th>( R_a (\mu m) )</th>
<th>( R_d (\mu m) )</th>
<th>( R_{sk} )</th>
<th>( R_{ku} )</th>
<th>( R_u/c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine blade</td>
<td>625</td>
<td>58</td>
<td>71</td>
<td>0.9</td>
<td>3.3</td>
<td>1.42e-2</td>
</tr>
<tr>
<td>2D aerofoil – light (leading edge and entire foil roughness)</td>
<td>191</td>
<td>24</td>
<td>28</td>
<td>0.5</td>
<td>2.6</td>
<td>8.36e-4</td>
</tr>
<tr>
<td>2D aerofoil – heavy (entire foil roughness)</td>
<td>446</td>
<td>13</td>
<td>22</td>
<td>2.4</td>
<td>14.7</td>
<td>1.95e-3</td>
</tr>
</tbody>
</table>
The BEM numerical model was run at $Re_c = 4 \times 10^5$ for the different roughness cases. The lift and drag coefficient data used are given in Fig. 10 for clarity. The uncertainty in the measurements is also indicated in this plot. These results, i.e. the reduction in lift coefficient and significant increase in drag coefficient, are similar to those for aerofoils intended for wind turbine applications [e.g. [12, 13]]. However, they are in contrast to the assumptions made by Batten et al. [6] in their BEM numerical model. Batten et al. assumed that blade roughness or fouling might increase $C_D$ by 50%, with no effect on $C_L$.

4.3. Turbine performance

The experimental turbine performance curves as a function of tip speed ratio are compared with numerical results from the blade element momentum theory for the smooth-bladed baseline case in Fig. 11. Each marker represents the average value for a single carriage run of approximately 30 s. Carriage speed was set to 1.68 m/s throughout the experiment and the tip speed ratio was adjusted by increasing the voltage input to the hysteresis brake. Tip speed ratios below 5.5 in the smooth blade case were unobtainable as the torque generated by the lift on the aerofoil was not enough to overcome the brake torque. The uncertainty at 95% confidence is indicated by error bars in each plot. A peak power coefficient of 0.42 occurs at a tip speed ratio of approximately 6 (Fig. 11a).

The numerical model was run using curve fits to the smooth $C_L$ and $C_D$ data obtained during the wind tunnel testing at both $Re_c = 4.2 \times 10^5$ and $Re_c = 5.2 \times 10^5$. The approximate operating point of the model turbine at maximum efficiency is $Re_c = 4 \times 10^5$. The numerical model at $Re_c = 4.2 \times 10^5$ accurately predicts the peak $C_P$ but slightly over-predicts for increasing tip speed ratios (Fig. 11a). Likewise, $C_T$ is accurately predicted in the operational range of the turbine, but tends to under-predict performance at higher $\lambda$ values (Fig. 11b). Both the over-prediction of $C_P$ and under-prediction of $C_T$ using BEM models were also observed by Bahaj et al. [22] and Batten et al. [6].

The lift and drag coefficients for the NACA 63-618 aerofoil used are Reynolds number independent for $Re_c > 5 \times 10^5$ (note that lift is also Reynolds number independent for $Re_c = 4 \times 10^5$), as shown in Fig. 8. The numerical model was run for $Re_c = 5 \times 10^5$ to demonstrate the changes in power and thrust coefficients for a Reynolds number independent turbine. The thrust coefficient is only
marginally affected by the increase in $Re_c$. However, there were discernible changes in the power coefficient. The increase in $Re_c$ caused a 2.5% increase in maximum $C_p$ and moved the optimum operating point from $\lambda = 6$ to $\lambda = 6.5$. The increase in $C_p$ was greater at higher $\lambda$, with a 16.5% increase at $\lambda = 10$. Thus in the optimal operating range of the model tidal turbine the results are very close to being Reynolds number independent and could be scaled to full-scale situations with minimal error.

The experimental turbine performance curves for the slimed and roughened cases are compared to the smooth-blade baseline case and to results from the numerical model at various roughnesses in Fig. 12. Case B, the lithium grease impregnated with diatomaceous earth applied to the turbine blades to mimic a biological slime, did not exhibit adverse behaviour compared to the clean case, as the majority of the applied fouling was sheared off during the first test leaving a very thin layer of grease on the blades. The remaining material improved the performance by delaying stall to higher angles of attack and allowing measurements at lower tip speed ratios than were attainable using the clean blades. The data obtained during the first run as the slime sheared off the blades was at $\lambda = 9.6$. This point has significantly lower $C_p$ and $C_T$ than the smooth bladed case. Biological slimes would attach to the blades more tenaciously than the lithium grease. To determine whether or not a biofilm would be able to withstand the shear

![Fig. 9. 2D NACA 63-618 roughened aerofoil (a) lift coefficient curves, (b) drag coefficient curves.](image)

![Fig. 10. 2D NACA 63-618 aerofoil data used for BEM numerical model (a) lift coefficient curves, (b) drag coefficient curves.](image)
forces on an operating marine current turbine, the shear stress on the blades was compared with the critical shear stress for biofilm removal.

The shear stress on the blades can be approximated by assuming a laminar boundary layer over the blades and using the Blasius approximation (equation (30)). The shear stress is then approximated by equation (31). At 70% of the span for $\lambda = 7$ the relative velocity is approximately 8.5 m/s, giving a Reynolds number of $3.6 \times 10^5$ and a boundary layer thickness of $3.4 \times 10^{-4}$ m. This results in a shear stress of approximately 25 Pa. A similar analysis on a full scale turbine results in a shear stress of approximately 6 Pa at 70% span. Finlay et al. [23] conducted an investigation of the adhesion strength of marine diatoms. They found that a critical shear stress of 1.3–1.4 Pa prevented the development of biofilm consisting of the diatom Navicula incerta on a glass substrate. In an earlier study, Schultz et al. [24] found that approximately 90% of Amphora cells were removed by a wall shear stress of 28 Pa, with 50% of cells removed with a shear stress of 5 Pa. These studies suggest that only limited biofouling would be present at the shear stress level found on the model turbine blades. However, biofilms could potentially withstand the shear stresses found on a full scale turbine blade under operating conditions. It is, however, difficult to

![Fig. 11. Performance of model scale marine current turbine – baseline case with smooth blades (a) power coefficient curves, (b) thrust coefficient curves.](image)

![Fig. 12. Performance of model scale marine current turbine under various roughened conditions (a) power coefficient curves, (b) thrust coefficient curves (note the numerical model for each roughness was run at Re = $4 \times 10^5$).](image)
make definitive statements in this regard as the tenacity of the biofilm is affected by a range of variables including, but not limited to composition, substrate, and a host of environmental factors.

\[ \delta = \frac{4.91x}{\sqrt{Re_x}} \]  

(30)

\[ r_{wall} = \frac{\mu U_{rel}}{\delta} \]  

(31)

Case C, the contact cement applied to the turbine blades, had significantly lower performance characteristics than the smooth-bladed case. The maximum power coefficient in this case was \( C_{P,\text{max}} = 0.34 \), a 19% reduction from the baseline case. The thrust coefficient at maximum \( C_T \) was reduced from \( C_T = 0.8 \) to \( C_T = 0.64 \), a reduction of 20%. Similarly to the Case B, data were able to be taken at lower tip speed ratios.

The numerical results from the blade element momentum theory are also shown in Fig. 12 for the three roughness scenarios run: leading edge light roughness, entire blade light roughness and entire blade heavy roughness. The numerical model does not exactly match the experimental results for Case C (contact cement applied to turbine blades) due to the difference in roughness between the turbine blades and the 2D aerofoil. The turbine blade had much higher absolute and relative roughnesses and a different roughness profile (evidenced by skewness and kurtosis values) than the heavy roughness applied to the 2D aerofoil. However, the trends exhibited by the experimental and numerical results concur. The presence of roughness on the turbine blades has an adverse effect on turbine performance and causes the entire power coefficient versus tip speed ratio curve to be offset below the smooth blade case. The numerical results provide very useful data on how the performance of a marine current turbine would be affected should the blades become roughened due to impact, cavitation or scour due to particulates or fouled with calcareous deposits such as barnacles.

The performance of a marine current turbine is very sensitive to the lift and drag coefficients of the particular aerofoil section used. This is particularly apparent when the leading edge and entire blade light roughness cases are compared. The entire blade case had only slightly reduced lift and slightly increased drag yet the impact on turbine performance, particularly in the operating range, was significant as shown in Fig. 12. The maximum \( C_T \) for light roughness applied to the entire blade was reduced by 4% and \( C_T \) at the operating point was reduced by 2% over the leading edge roughness condition.

The numerical light and heavy roughness curves were shifted downwards on the plots. The tip speed ratio at the maximum \( C_P \) was also shifted towards higher \( \lambda \) with increasing roughness. The reductions in maximum \( C_P \) from the smooth case were 5.5% and 20% for the light and heavy roughnesses, respectively. These results are very different to those presented by Batten et al. [6]. They assumed that blade roughness or fouling might increase \( C_P \) by 50%, with no effect on \( C_L \). Hence their model predicted a much smaller decrease in \( C_P \) of 6–8% due to roughness at high \( \lambda \) and their entire curve was not shifted below their smooth case.

5. Conclusions

A model horizontal axis marine current turbine was tested in a towing tank under smooth and artificially roughened blade conditions. The turbine performance was predicted using blade element momentum theory informed by wind tunnel testing of the NACA 63-618 aerofoil section used for the turbine blades in both clean and roughened conditions. The wind tunnel testing showed that roughness on the NACA 63-618 aerofoil affects both the lift and drag coefficients. Lift and drag data for the leading 10% of the chord roughened were very similar to data for the entire aerofoil roughened, which highlights the significance of leading edge roughness for the NACA 63-618 aerofoil.

The presence of roughness on a marine current turbine blade can significantly reduce the performance of the turbine. Experimental results gave a 19% reduction in maximum \( C_P \) and a downward shift in the entire curve. Similar results were found for the numerical model. 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 \( \lambda \) than were attainable using the clean blades.

The model marine current turbine was operating in a regime that was Reynolds number independent for lift, and very close to Reynolds number independent for drag. The results can be scaled to full-scale situations with minimal error at the optimal operating range. The experimentally validated numerical model based on the blade element momentum theory accurately predicts the power and thrust coefficients for the smooth-bladed case. It provides new data on turbine performance under roughened conditions and is a valuable tool for turbine researchers, designers and operators. The results can be used to support large scale dynamic modelling studies, such as those used to predict tidal power extraction [e.g. [25]].

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References


