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The impact of diffuser augmentation on a tidal stream turbine

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ABSTRACT

The results from an experimental study of a model diffuser augmented tidal stream turbine are presented with a particular focus on the impact of the diffuser upon the turbine's performance in yawed flows. This study is the first to examine yaw effects with quantification of blockage corrections and is the first study of the wake recovery characteristics of such devices. The device was designed using an innovative optimisation procedure resulting in a diffuser that was able to maintain the turbine's performance to yaw angles of up to $\pm 30^{\circ}$. It is shown that the diffuser's performance is strongly influenced by its length to diameter ratio and by the jet flow that develops through the turbine's tip gap. Although the performance characteristics of an individual turbine can be significantly improved by diffuser augmentation under yawed flow, a wake recovery rate that is less than half that of a bare rotor raises doubts about their suitability for array deployment.

1. Introduction

It is estimated that the UK could produce 15–20% of its electricity demand from tidal resources (Callaghan, 2006). With such a large resource available there has been increased research in tidal stream generation. The conversion technology is at an early stage of development and questions remain regarding the design, cost and productive capacity of such devices.

Much of the existing conversion technology used for tidal stream generators has its origin in the wind energy industry (Fraenkel, 2002; Batten et al, 2007; Bahaj et al., 2007). Many possible device configurations have been proposed with horizontal axis turbines receiving most research attention (Khan et al., 2009).

Diffuser augmentation of wind turbines has been mooted since the late 1970s (Flay et al., 1998) and there is experimental data which demonstrates potential performance enhancements (Igra, 1977, 1981; Flay et al., 1998, Phillips, 2003; Abe et al., 2005; Ohya et al., 2008; Ohya and Karasudani, 2010). This concept has been largely rejected as impractical due to structural loadings, associated costs, doubts over generation performance and visual intrusion (Lawn, 2003; van Bussel, 2007; Gaden and Bibeau, 2010). For smaller, less visually intrusive tidal turbines, in a predictable flow regime, the case for diffuser augmentation is stronger. Questions over the fluid dynamics and performance of diffuser augmented devices remain however.

The study of diffuser augmented tidal stream devices has been approached by a number of authors who looked to maximise the power output (Munch et al., 2009; Gaden and Bibeau, 2010; Shives and Crawford, 2010; Belloni and Willden, 2011; Fleming et al., 2011; Luquet et al., 2011; Reinecke et al., 2011). Secondary characteristics which affect the power generation capabilities of diffuser augmented tidal stream devices, such as performance in yawed flows and wake recovery have not been investigated however.

Research into the yaw performance of diffuser augmented wind turbines has been presented by a number of authors (Kogan and Seginer, 1963; Foreman and Gilbert, 1979; Igra, 1981; Phillips, 2003). There is agreement that diffusers maintain device performance at yaw, but the producing mechanism and extent are disputed. Igra (1981) stated that the performance is due to an increase in “lift” from the diffuser's annular wing section, whilst Phillips (2003) stated that it was due to the slotted design of the diffuser, with the slot flow increasing boundary layer momentum. The range of angles over which the performance is maintained extends from $\pm 15^{\circ}$ (Phillips, 2003) to $\pm 30^{\circ}$ (Kogan and Seginer, 1963), with no agreement reached on the performance mechanism. There are also questions raised by the authors about the validity of the findings, since in many cases the devices caused a significant blockage within their respective test sections, with no corrections applied (Igra, 1981; Phillips, 2003).

Wind turbine wake structure has been studied extensively, with summaries presented by Crespo et al. (1999), Vermeer et al. (2003) and Sorensen (2011). The wake structure of horizontal axis tidal stream turbines has also been the subject of study (Bahaj

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et al., 2007; Harrison et al., 2009; Maganga et al., 2010; Myers and Bahaj, 2010; Turnock et al., 2011; Mycek et al., 2014). The wake of a diffuser augmented turbine has received little attention, with the experimental and numerical work of Abe et al. (2005) and Ohya et al. (2012) respectively, on the flow within the cavity of a flanged diffuser structure and that of Grumman Aerospace (Oman et al., 1977) on the exit plane flow of a multi-slotted diffuser being the only studies to the author's knowledge. These studies concentrated on the flow within the cavity and immediately post-exit, but the study of the far wake of a diffuser augmented turbine has not previously been attempted.

This paper investigates the effects of flow yaw on the performance of diffuser augmented turbines and examines the factors which drive this. It also examines the effect of diffuser augmentation on wake propagation and recovery. The implications of these properties of diffuser augmented devices on power generation are also discussed.

2. Experimental methodology

2.1. Test facilities

Testing was undertaken in the 2 m^2 wind tunnel of the School of Engineering at Durham University. The tunnel is a 3/4 open-jet, open-return wind tunnel with an inlet contraction ratio of 7.7:1. The wind tunnel is fitted with an under floor turntable and a three axis overhead gantry traverse system, which is used to control the position of a five hole pressure probe. The maximum blockage in the tunnel, when the diffuser and rotor were operated together, results in a jet area blockage of 9.8%. For the tunnel type and dimensions used the blockage corrections to the velocity field are of the order of 1.18% (Garner et al., 1966; Ewald, 1998).

2.2. Apparatus

The turbine was attached to an AXI5330/24 three phase permanent magnet motor, which was connected to a traverse controlled, coil based variable resistance bank to enable speed control and power takeoff. The motor was attached to an Omega TQM301 reaction torque transducer. The rotational speed was captured using an Optek OPB704 reflective phototransistor, triggered by markings on the drivetrain.

Pressure measurements were taken using Sensortechnics HCLA12X5DB transducers attached to the surface static pressure tappings via pressure tubing. The five hole probe was operated as detailed by Oettle (2013). All data were logged using a National Instruments USB6218 datalogger at a frequency of 2048 Hz.

2.3. Rotor geometry

The rotor geometry was designed to be representative of current designs whilst remaining as simple as possible for ease of modelling and construction. The rotor had three blades, with a tip radius of 174 mm. The blades were constructed from ABS plastic using a Makerbot Replicator, and polished for a smooth surface finish. The blades were developed from a NACA63818 blade section, with a rounded trailing edge to facilitate manufacture. The geometry of the blade section can be seen, along with the NACA63818 section in Fig. 1, with the section's lift and drag performance obtained through CFD analyses in Fig. 2. The CFD simulations were performed in 2D on a structured mesh using ANSYS Fluent with the Transition SST turbulence model and full details of these are given by Cresswell (2015). The details of the blade design, with the linear distributions of blade chord (c) and pitch can be seen in Table 1.

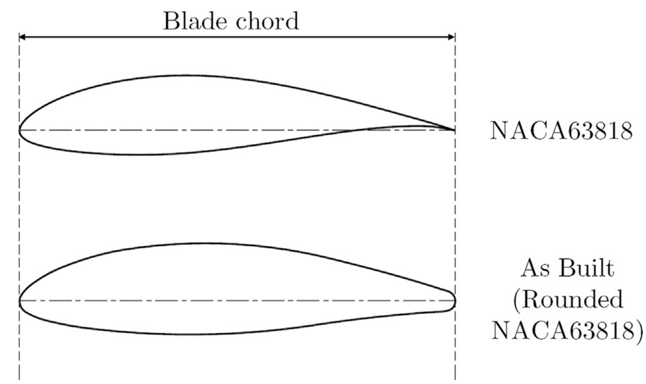

Fig. 1. NACA63818 and as built blade cross sections.

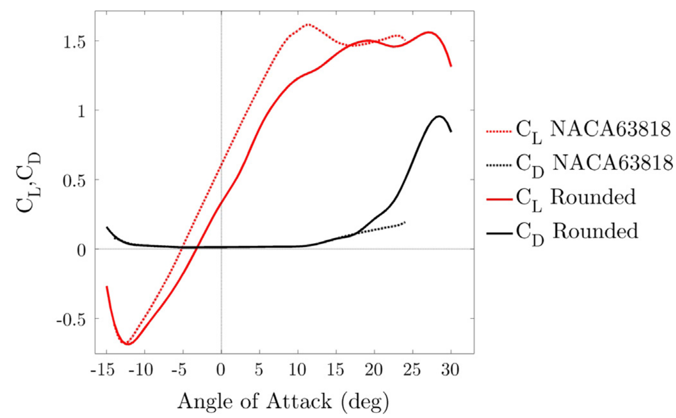

Fig. 2. NACA63818 and rounded NACA63818 lift and drag coefficients against the angle of attack at a Reynolds number of 2.45×10^5 (Cresswell, 2015).

Table 1
Blade geometry details for the experimental blade sets.

r/R_{Ro}	c/R_{Ro}	Pitch (deg)
0.20	0.143	29.49
0.30	0.137	26.12
0.40	0.131	22.74
0.50	0.126	19.37
0.60	0.120	16.00
0.70	0.115	12.62
0.80	0.109	9.25
0.90	0.103	5.87
1.00	0.098	2.50

2.4. Diffuser geometry

The diffuser geometry was created using an optimisation based around CFD, a Kriging surrogate model and a genetic algorithm. Use of a surrogate model and genetic algorithm allows for reduced computational time compared to a genetic algorithm alone (Jeong et al., 2005; Li, 2008).

The device is a uni-directional diffuser augmented horizontal axis tidal turbine, which was assumed to be mounted at mid-depth of a tidal channel. The depth of the channel was taken to be 30 m, which is the mean channel depth in which it is possible to drive monopile foundations (Fraenkel, 2007). Fig. 3 shows the assumed tidal channel and referenced dimensions. The diameter of the device was determined by the need for rotation to face the reversed tidal current, under the constraint that there should be a clearance of 2 m between the device, the seabed and the free surface during rotation and 5 m during operation.