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Analysis of bi-directional ducted tidal turbine performance

Conor F. Fleming [*], Richard H.J. Willden

Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK

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ABSTRACT

Several commercial tidal turbine designs feature axial flow rotors within bi-directional ducts. Such devices are typically intended to increase power extraction through a flow-concentrating effect, operating on flood and ebb tides without a yawing mechanism. Research focused on such devices has been limited so far, with available results indicating poor performance relative to bare rotors. This study further investigates the relative performance of bi-directional ducted tidal turbines in confined flow.

Several duct profiles are evaluated relative to unducted rotors using the Reynolds-averaged Navier–Stokes solver ANSYS Fluent. The rotor is represented as an actuator disc, which mimics the streamwise thrust of a real device but does not reproduce its swirl or additional turbulence generation. This idealised model achieves optimal energy extraction and enables fair comparison of duct geometries. Device power is reported relative to total frontal area, reflecting the fact that the overall dimension of the device will be limited by water depth. Comparisons based on rotor area show how the absolute power is increased by a duct, but that this is attributable to an increase in blockage.

The fundamental effect of a duct on a rotor, as well as the secondary effects of duct camber and thickness, are identified by analysing streamwise distributions of velocity, pressure and cross-sectional area along the rotor streamtube. Ducts are found to limit the expansion of the downstream flow, in turn restricting the pressure reduction immediately behind the rotor. This effect, in combination with the reduced volumetric flux through a ducted rotor relative to a bare rotor, results in reduced power extraction.

The effects of duct curvature and thickness on turbine performance are also examined. Where a ducted rotor is desirable, e.g. for the protection of rotor blades, a thick profile with slight curvature performs best.

1. Introduction

There has been renewed focus on renewable energy in recent years due to the increasing environmental cost of energy derived from fossil fuels. Tidal currents are an attractive source of renewable energy due to their predictability and the low visual impact of tidal stream energy converters. This industry is in its infancy, with few devices in operation commercially (e.g. the Seagen turbine in Strangford Lough, Northern Ireland) and a variety of prototype designs under trial at various locations including the European Marine Energy Centre in the Orkney Islands, UK.

Turbine designs can be broadly categorised into axial flow (similar to conventional wind turbines), cross-flow (similar to Darrieus wind turbines), and oscillating types. An axial flow turbine may feature a duct, which has been suggested by

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[*] Corresponding author at: Atkins, Woodcote Grove, Epsom KT18 5BW, UK.
E-mail address: conor.fleming@oxon.org (C.F. Fleming).

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manufacturers [1,2] to have advantages over a bare rotor in terms of power generation, realignment of yawed flow and protection of rotor blades.

Uni-directional ducted turbines have attracted academic and industrial interest for many decades, notably in the experimental work by Foreman et al. [3,4] which formed the basis for the later attempted commercialisation of a ducted wind turbine [5]. They typically feature a diffuser downstream of the rotor, intended to increase the pressure drop across the rotor and also increase the mass flux through the rotor, improving power extraction from the flow. Comprehensive reviews of research into uni-directional ducted devices are presented by Shives and Crawford [6] and Belloni [7].

Bi-directional turbines have received attention more recently in the growing tidal energy industry due to their suitability for operation in tidal currents. These turbines are symmetric about the rotor plane, and typically feature a converging-diverging nozzle which is intended to accelerate the flow through the rotor and hence increase the available kinetic energy flux. Such devices developed in the last ten years include the current Rotech Tidal Turbine by Lunar Energy [2], the OpenHydro turbine [1], the Solon turbine by Atlantis Resources Corporation (discontinued in 2013) [8] and the Clean Current tidal turbine (discontinued in 2015) [9]. Despite the industrial interest in bi-directional ducted rotors, little research published to date has focused on this topic. Setoguchi et al. [10] test a range of bi-directional ducts, and examine the effect of the outer surface profile on internal flow acceleration. However a rotor is not represented in their experiments, and its presence would clearly impact the balance between the flow accelerated through the duct and the flow forced to pass around the outside of the duct. In a precursor to the present study, the authors designed a bi-directional ducted turbine based on a parametric computational study of a selection of candidate profiles [11]. The unducted rotor was found to yield a power coefficient approximately 75% higher than the best-performing ducted rotor, when power was normalised on total device area (including the duct where present) and under consistent blockage conditions (blockage is defined as the ratio of total device frontal area to the flow channel cross-sectional area). Similar findings are reported by Belloni et al. [12,13], who simulate a ducted and an unducted device in confined flow. The power coefficient for the unducted turbine is roughly 50% greater than that of the ducted turbine when based on device total area, although they found power density (power per unit rotor area) to increase. They identified two operating modes for bi-directional ducted turbines. At low rotor resistance, the flow remains attached throughout the device. The velocity through the rotor is significantly increased, but power remains low due to the low level of rotor thrust. As rotor resistance is increased the approaching flow is significantly diverted around the duct, leading to external separation at the duct leading edge. For the blockage conditions simulated, the external separation led to an increase in the effective blockage of the flow, which led to an increase in extracted power in accordance with the known effects of flow confinement [14]. However, if the rotor resistance is overly high, the benefit of leading edge separation is lost and too much flow is diverted around the device. The authors also note the reduced hydrodynamic efficiency of ducted turbines due to the additional thrust exerted by the duct.

This paper further explores the fluid mechanics of bi-directional ducted turbines. A series of duct profiles are devised to explore the effects of duct curvature and thickness on turbine power and hydrodynamic efficiency. Each device is simulated at a range of operating points using the Reynolds-averaged Navier–Stokes (RANS) equation solver ANSYS Fluent, following a modelling approach similar to that of Shives and Crawford [6]. Flow conditions within each duct are necessarily a function of duct geometry and as such optimal rotor geometry will be different for each duct [15]. To make fair comparison between ducts we therefore use an actuator disc representation of the rotor. An actuator disc is an idealised, one-dimensional representation of a rotor, where thrust is applied against the flow in the axial direction by a thin disc. The power extracted from the flow by an actuator disc is simply the product of the axial thrust and the flow velocity at the disc, $P = T_{\text{disc}} u_{\text{disc}}$. The simulations presented in this paper therefore represent the upper limit of power extraction by each duct, enabling comparison independently of rotor design. We identify trends in power and hydrodynamic efficiency and their causes are explained by reference to streamwise profiles of streamtube velocity, pressure and cross-sectional area.

2. Ducted turbine design generation

A series of duct geometries are devised within particular constraints, so that the effects of curvature and thickness may be explored. The first constraint imposed is that all devices are compared under consistent blockage conditions. Various authors have highlighted the sensitivity of turbine power and thrust to blockage [16–18], and it is essential to eliminate this effect from the comparison of duct geometries. The blockage ratio chosen for the current study is $B = 0.131$. This corresponds to a fence of turbines with lateral centre-to-centre spacing of three rotor diameters (D) apart laterally in water of depth $2D$ although note that, as discussed in Section 3, the actual channel geometry as implemented in the simulations was axisymmetric.

The second constraint is that the duct should be symmetric about the rotor plane to allow bi-directional operation without any yawing mechanism.

Thirdly, we limit the scope of this study to the effect of duct profile, and hence choose a single ratio of duct length L to diameter D for all duct designs. Our choice of $L/D = 1$ is a moderate value based on observations of commercial designs [1,2,9].

Finally, all curved surfaces are constructed from circular arcs. This is a compromise between simplicity of design and manufacture, where straight sections and corners might be preferable, and hydrodynamic considerations, where a smooth profile is favoured. Additionally, the use of simple arcs allows for the current duct geometries to be reproduced.