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Hydrodynamic analysis of a ducted, open centre tidal stream turbine using blade element momentum theory

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ABSTRACT

This paper analyses two different configurations of horizontal axis Tidal Stream Turbines (TSTs) using a Blade Element Momentum Theory (BEMT) model. Initially, a ‘conventional’ three bladed and bare turbine is assessed, comparing against experimental measurements and existing literature. Excellent agreement is seen, increasing confidence in both the implementation of the theory and the applicability of the method. The focus of the paper lies on the analysis of a ducted and open centre turbine. An analytical adjustment to the BEMT model is applied, using empirical expressions detailed in the literature which are devised from Computational Fluid Dynamics (CFD) studies. This is modified to a symmetrical duct profile, calibrating certain geometrical parameters against blade resolved CFD studies of a bi-directional device. The results are validated with a coupled CFD blade element model (RANS BEM), where both models align very closely (within 2%) for most tip speed ratios (TSRs), including the peak power condition. Over predictions are seen at higher TSRs of up to 25% in power and 13% in thrust at TSR = 5, due to model limitations in replicating fully the complex flow interactions around the hub and the open centre. The presented approach benefits from significantly lower computational requirements, several orders of magnitude lower than reported in the RANS-BEM case, allowing practicable engineering assessments of turbine performance and reliability.

1. Introduction

Tidal Stream Turbine (TST) technology has been in the early stage developmental phase for a number of years, as engineering challenges in designing for extreme operating environments, combined with political and environmental factors has limited the rate of maturity. One of the earliest landmark projects was the MCT SeaGen, a 1.2 MW twin rotor device installed in the Strangford Loch, Northern Ireland in 2008, due to be decommissioned this year after generating 10 GW h electricity (ReNews, 2016). Despite hindrances in the industry, recent progression has led to the deployment of full scale arrays around the UK and France. Although there are many designs of tidal energy converters, the industry appears to have converged upon two configurations, which have seen the furthest advancement to date in terms of commercial scale deployment.

The first is a ‘classical’, 3 bladed horizontal axis design, similar to its wind turbine counterpart. The MeyGen project phase 1A (MeyGen, 2016) has seen the installation of its first three turbines of a 6 MW array as of January 2017 in the Pentland Firth, Scotland (shown in Fig. 1-1).

The second is a high solidity, ducted and open-centre turbine design. Ducts are primarily designed to increase the power extraction by increasing the mass flow rate through the rotor. Additional benefits include aligning yawed flow, providing a housing for a direct drive rim generator and removing the requirement for mechanical systems such as a gearbox. DCNS/OpenHydro have installed a pair of 500 kW rated capacity turbines (shown in Fig. 1-2), as a demonstration array in Paimpol-Bréhat, Northern France, in collaboration with EDF.

Hydrodynamic assessments are performed in order to gain insight into various aspects of the turbine. An extensive range of numerical models exist, each designed to perform different tasks and selected depending on the area of interest or objective of the study. Highly

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Fig. 1-1. Andritz Hydro Hammerfest 1.5 MW rated TST with installation into the Pentland Firth, Scotland (images credit: Atlantis Resources Ltd.) as part of the MeyGen Phase 1A deployment.

complex, high fidelity models are commonly used in design refinement, or to perform detailed assessments of turbine components under specific operating conditions. These can also be used to determine wake formation to measure the impact of the turbines on the tidal flow, as well as to describe the interactions of multiple turbines in an array.

Simpler models employ a more basic approach which are able to compute the force distributions along the rotor blades, and determine the overall performance of a turbine, aiding early stage decision making on optimal device designs for specific sites. Significantly lower computational requirements and fast processing time can be exploited for engineering applications where many analyses are required, such as performing numerous design iterations, analysing multiple or varying inflow conditions, or assessing fatigue loading.

Several industrial and academic codes are based on BEMT, (Batten et al., 2007; Masters et al., 2011; DNV GL Garrad Hassan, 2012) among which is a commercial standard software tool, 'Tidal Bladed', by the classification society DNV-GL. Despite the simplified approach, these models are well established and reliable, based on experience from the wind turbine industry. The BEMT code developed in this study is initially applied to a bare, 3-bladed turbine, where a full validation study is detailed in Allsop et al. (2016). However, the availability of such models for ducted, high solidity and open centre turbines is limited. At present, these types of devices are analysed using blade resolved CFD, which has a high computational requirement and is therefore not practical for multiple calculation applications. Less computationally intensive alternatives have been applied (Fleming et al., 2011; Turnock et al., 2011; Belloni et al., 2016) based on a coupled Reynolds Averaged Navier Stokes with blade element momentum (RANS-BEM), where case studies report good comparison with fully blade resolved studies, at a fraction of the processing time (McIntosh et al., 2012).

This paper aims to assess the performance of an analytical/empirical methodology to account for the presence of a duct, which is implemented within a BEMT code. This ducted BEMT model is applied to a bi-directional ducted turbine and results are compared with those of a coupled RANS BEM simulation.

The remainder of this paper is structured into 5 main sections: i) a brief outline of the underlying theory considered in the model; ii) the setup and implementation of the numerical model; iii) main results for the three bladed and ducted, open centre turbine; iv) a discussion comparing the different numerical models and implications as well as v) a conclusion of the main findings and recommendations for further work.

2. Methodology

The principles of BEMT are well defined in the literature, where this section aims to give a brief outline of the methodology. For further details and full derivations, the reader is referred to the following texts (Burton et al., 2011; DNV GL Garrad Hassan, 2012; Moriarty and Hansen, 2005).

Section 2.1 describes the BEMT model for a classical 3 bladed, bare turbine, with Section 2.2 outlining the adaptations based on an analytical framework to account for the presence of a duct. Section 2.3 defines output parameters that are used to validate the two models, with Sections 2.4 and 2.5 defining various correction factors in order to account for physical occurrences that are neglected in the BEMT.

2.1. Blade element momentum theory

One-dimensional momentum theory models the turbine as an infinitely thin, semi-permeable actuator disc exerting zero friction,

Fig. 1-2. DCNS/OpenHydro 500 kW rated turbine with installation at the Paimpol Bréhat site, Northern France (images credit: DCNS/OpenHydro).