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A BEMT model for a high solidity, hubless and ducted tidal stream turbine

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Summary: A Blade Element Momentum Theory (BEMT) model for 'conventional' 3 bladed designs of Tidal Stream Turbine (TST) is presented, with validations from scale model experiments carried out in a cavitation tunnel. Assumptions and limitations of the model are discussed in order to gauge potential use in assessing a high solidity, hubless and ducted TST design, which has been developed by OpenHydro. A number of adjustments to the model are considered, which are to be validated with fully blade resolved CFD studies and field data from a full scale device deployed at Paimpol-Bréhat, Brittany at the start of 2016 in collaboration with EDF.

Introduction

BEMT is a simple, fast processing and low computationally demanding method to predict the performance and thrust loading of a turbine. Commonly used in the wind industry, adaptation has more recently occurred in TST modelling, with academic and commercial models developed (e.g. [1] [2]). These are, however, limited to application with 'conventional' 3 bladed turbine designs, and unsuitable to assess high solidity, hubless and ducted designs. The objective of this study is to present a BEMT model developed for a 'conventional' TST, and discuss adjustments to assess an alternative configuration designed by OpenHydro in its latest generation 2MW device.

Methods

This study has developed a BEMT model, where the turbine is modelled as a frictionless, infinitely thin, semi-permeable actuator disc within a stream tube. Axial and tangential induction factors as well as flow angles of attack can be formulated based on the reduction in axial momentum on the flow as a result of the disc presence and the increase in tangential momentum due to the disc imparting rotation on the flow. The disc is split into a number of concentric annuli, where each section of the blade is taken as an independent 2D aerofoils and blade forces can be determined as a function of foil lift and drag coefficients. An iterative solver computes the angle of attack, induction factors and blade forces, and converges on a solution where equilibrium is achieved.

Correction factors have been applied including a Buhl factor for highly loaded conditions, and a Glauert factor to account for losses at the tip and hub. Inputs into the model include fluid properties, flow parameters and turbine geometry to replicate validation case conditions. Aerofoil coefficients are generated using a combined linear vorticity stream function panel method incorporating a viscous boundary layer. Du-Selig and Eggers models account for stall delay on a rotating foil, with post stall values attained using a Viterna extrapolation function.

To account for tunnel boundary layer effects a shear profile is applied to the inflow using a 1/7th power law, showing excellent agreement with flume data from a channel at EDF. Blockage corrections have been applied to the experimental coefficients and TSRs, to account for channel effects [3], converting results to 'equivalent open water' values for direct comparison with the model.

Results – Conventional Device

Coefficients of power (CP) and thrust (CT) curves for varying tip speed ratios (TSR) are shown in Figure 1.

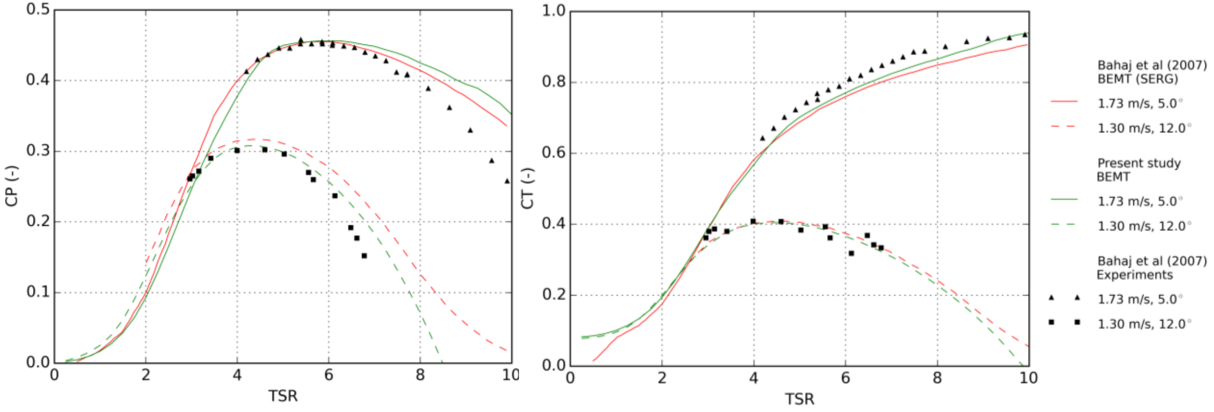

Figure 1 Power and thrust variation with TSR for a scale model TST from BEMT analyses and experimental data

Results from this study show good agreement with experimental data, and are consistent with another BEMT model [4]. At 1.73m/s flow, the models show an over prediction in power at high TSR, considered due to errors in large blockage factors applied to the experimental data [3].

Discussion – OpenHydro Device

Figure 2 shows the OpenHydro 2MW configuration to be analysed, with main differences including high solidity, open centre, hubless rotor and ducted flow. The following points discuss potential changes to the code to account for the new configuration, which are currently under investigation using CFD studies.

The one dimension flow assumptions neglect the radial flow that occurs due to the tendency of a fluid to flow around the blade tips from the pressure to the suction side or the rotor. This span wise flow reduces the hydrodynamic efficiency at the tip and hub, and can be approximated using an analytical solution proposed by Pandtl (Figure 3), taking the helical sheets as a succession of discs travelling at an average velocity of the wake and free stream. The new configuration sees blades reversed in orientation, with tips now facing towards the rotor centre, and the roots connected by the outer ring housed in the stator. A change in the formation of the vortex sheets requires a new tip/hub loss factor to be applied.

The modelling of an actuator disc in a stream tube predicts an unphysical reversal of flow in the wake at axial induction factors (a) greater than 0.5. This means that the increased thrust forces that occur at $a \geq 0.4$ (known as the highly loaded regime) are not predicted using this method. The Buhl correction factor is applied in this condition, a semi-empirical parabolic function based on Glauert's experiments with semi-permeable discs. For the 'conventional' design, highly loaded conditions are only seen at the near tip elements at high flow rates. As loading increases with decreasing disc permeability, high solidity designs will operate more in this regime (see Figure 4) and as a result will be have a higher sensitivity to experimental errors or inaccuracies.

The presence of a duct increases the inflow velocity at the rotor and restricts wake expansion, therefore impacting the assumptions of flow bounded by a stream tube. Combined Reynolds Average Navier Stokes (RANS) BEM models have been developed, able to represent the flow through the duct and open centred turbines [5]. In order to implement this into BEMT, a correction factor is considered based on similar blockage approximations of flow in a channel proposed by [6].

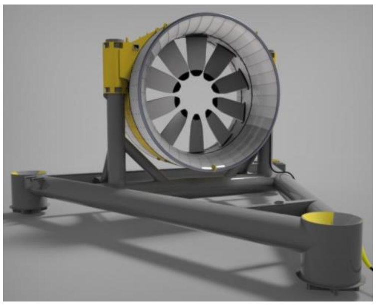

Fig. 2 OpenHydro latest generation 2MW device [7]

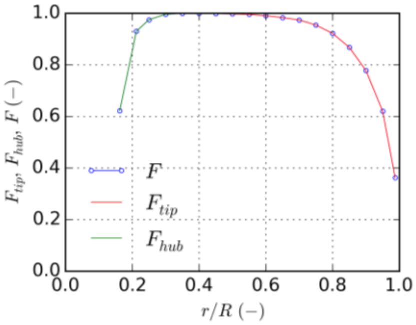

Fig. 3 Blade distribution of tip/hub loss factor for a conventional device at TSR 5

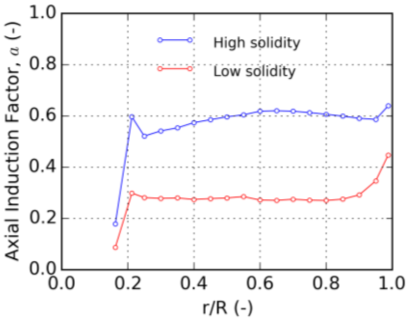

Fig. 4 Blade distribution of axial induction factor at TSR 5

Acknowledgements:

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