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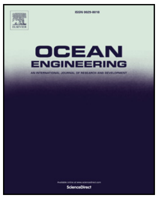

Blade element momentum theory for a tidal turbine

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ABSTRACT

A key hydrodynamic difference between tidal current and wind turbines is the volume-flux constrained flow field in which tidal turbines operate and the resulting streamwise static pressure difference that develops in the flow passage. Blade Element Momentum (BEM) theory is extended to account analytically for the effects of blockage and the development of the static pressure difference in the flow passage and shows agreement in thrust and power predictions to within $\pm$ 3% of equivalent blade resolved simulations. The confined flow BEM model is employed to study two different power capping strategies: varying the rotational speed with fixed pitch blades; and pitching the blades to feather at constant rotational speed. Pitch-to-feather achieves reduced thrust above rated flow speed which leads to a greater extractable resource than achievable with overspeed control, due to the feedback between device thrust and available tidal resource. Flow confinement is shown to reduce the flow speed at which rated power occurs, and increases the rotor loads and power below rated conditions. It is also shown that root bending moments, which affect fatigue damage rates, increase with flow confinement.

1. Introduction

The adaptation of established techniques for the analysis of wind turbines has allowed much progress to be made in the understanding of axial flow tidal current turbines. The analysis of an actuator disc in a confined flow field by Garrett and Cummins established the importance of the blockage ratio, B, the ratio of rotor swept area to the cross sectional area of the surrounding flow passage (Garrett and Cummins, 2007). It was shown that the maximum power coefficient of an actuator disc increases by a factor of $(1-B)^{-2}$ above the Lanchester-Betz limit of 0.593 when blockage effects are considered, allowing tidal current turbines to achieve higher power coefficients than wind turbines. Physically, this is because a static pressure drop is established in the blocked flow between far upstream and downstream of the turbine, allowing a greater pressure drop to be supported across the turbines, thereby increasing the peak thrust and extractable power as the local blockage ratio increases. Whereas the maximum extractable power for a wind turbine is achieved by reducing the flow speed through the turbine plane to two thirds of its upstream value, for a tidal turbine maximum power occurs at a monotonically reducing flow speed through the turbine plane as the blockage ratio is increased. Furthermore, as the blockage ratio increases and the bypass flow passage becomes more constrained, the flow speed bypassing the turbine increases (Vogel et al., 2016).

There has been interest in the fields of both the wind and tidal stream energy in understanding and quantifying the effects of flow confinement on rotor performance, such as those encountered in wind tunnels and water flumes. Experimental investigations of tidal rotors have confirmed the uplift in rotor thrust and power that occurs with increasing blockage ratio (Bahaj et al., 2007), and Chamorro et al. (2013) demonstrated that blockage effects can increase spanwise flows along rotor blades and increase the level of rotor-induced turbulence in the wake. Similar dependence on blockage has been observed for wind turbines in tunnels, with Sarlak et al. (2016) noting that the significance of the effects also depends on rotor thrust. Understanding the effect of blockage on rotor performance has particular importance for rotor design, as increased blade loading can result in larger root bending moments (Ouro et al., 2017), as well as allowing the for possibility of improved device performance if inter-turbine spacing is carefully controlled to exploit constructive interference effects between turbines through flow confinement (Bai et al., 2013; Vogel and Willden, 2017).

The change in flow conditions due to blockage effects can be related to turbine performance, given rotor properties such as aerofoil lift and drag coefficients, and blade twist and solidity using Blade Element Momentum (BEM) theory. BEM theory has been widely used for wind turbine analysis and design, and has increasingly been applied to tidal current turbine analysis and design. BEM theory, as applied to wind turbines, does not consider the effect of blockage on rotor performance. One approach for addressing this in the context of tidal turbines has been to embed the blade element analysis within a computational fluid

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dynamics (CFD) simulation, where the blade element model is unchanged from that for wind turbines and the effect of the constrained flow field is simulated explicitly to account for blockage effects (for examples, see Masters et al. (2011), Schluntz and Willden (2013), and Edmunds et al. (2014)). An alternative to performing blade element-CFD simulations is to modify the momentum equations in BEM theory to take the effects of blockage into account, such as by using the models presented in Garrett and Cummins (2007) or Whelan et al. (2009). A blockage-corrected analytic BEM model provides a tractable tool which may be used in the design and analysis of tidal turbines. In particular, a blockage-corrected BEM tool provides an efficient method for investigating the multitude of design cases necessary to develop a robust rotor design, such as rotor performance in off-design conditions, performance during power capped operation, and rotor design in blocked conditions. Turbine design in blocked conditions is particularly important if designs are to approach the higher power coefficients predicted by the simple analytic theory of Garrett and Cummins.

This paper develops a blockage-corrected BEM model using the rigid lid momentum model of Garrett and Cummins to provide a semi-analytic tool which is validated against blade boundary layer resolved simulations. The blockage-corrected tool allows the rapid exploration of the blockage and tip speed ratio operational space of turbines, and is used to investigate the performance of rotors in blocked conditions. The rotor characteristics (performance as a function of flow speed) determined with such an analytic BEM method allow long turbine fences to be simulated without the need for expensive three dimensional numerical models by providing sub-grid scale turbine models suitable for depth-averaged simulations.

2. Effect of blockage on momentum theory

Wind turbines are generally modelled as operating in unconfined flows in which there is full recovery of the static pressure far downstream of the rotor. Garrett and Cummins showed with Linear Momentum Actuator Disc Theory (LMADT) that momentum removal from a constant volume-flux flow by a turbine results in a static pressure deficit in the far wake of the rotor, and hence a static pressure gradient is established in the flow passage containing the turbine (Garrett and Cummins, 2007). This static pressure gradient results in a greater achievable pressure difference across the rotor plane as compared to unblocked flow. There is hence a greater flow speed through the rotor plane of the blocked rotor for a given level of thrust, which generally increases the torque and therefore the power, depending on the angle of attack of the blades.

The flow speed through the rotor plane and in the wake of the rotor depends on the applied thrust and blockage ratio, and consequently the momentum equations within the unconfined BEM formulation must be modified to account for this additional dependency. The changes to momentum theory for the confined flow case are outlined herein; a detailed account of unconfined BEM theory may be found in Burton et al. (2001).

Fig. 1 is a schematic of the flow past a rotor in a volume-flux constrained flow. The upstream boundary of the confined BEM model is derived from the larger-scale flow around the turbine, which may, for example, be the flow through a fence of turbines that is being simulated in a depth-averaged coastal scale model. This provides the upstream flow speed, u_a, which is taken as the reference velocity for the turbine-scale model. The flow through the rotor swept area is divided into N independent annular streamtubes of width δr, which are bounded by the bypass flow. The downstream boundary of the finite blockage BEM model is the streamwise point at which the static pressure equalises across the annular streamtubes and the bypass flow, although the possibility of differing flow speeds between the bypass and each annular streamtube is allowed.

The flow past the rotor is analysed at four stations; station one, which is far upstream of the rotor and unaffected by its operation (at least within this turbine-scale model), station two, which is immediately upstream of the rotor, station three, which is immediately downstream of the rotor, and station four, which is far downstream of the rotor at the position where static pressure may be considered as having equalised between the core and bypass streamtubes. The mixing processes between the core and bypass flows, which result in further energy removal from the flow, are assumed to occur entirely downstream of station four, and result in a uniform flow with speed identical to that far-upstream, as shown by Garrett and Cummins (2007). Energy extraction from a sub-critical open channel flow implies that the free surface elevation must decrease slightly far downstream. This phenomenon is negligible for the range of Froude numbers (0.10–0.20) at sites of interest for tidal stream energy, although could be incorporated into the analysis using computational models or momentum theory that includes free surface deformation, e.g. Houlsby and Vogel (2016). Assuming no other work is done on the fluid, momentum removal by the rotor results in a static pressure drop between stations one and four of $\Delta p = p_1 - p_4$. The induction factors used to describe the velocity u_{2di} through the i^{th} streamtube at the rotor plane, a_{2i}, and the velocity u_{4di} in the wake of the turbine, a_{4i}, are defined relative to the reference flow speed u_a:

$$u_{2di} = (1 - a_{2i})u_a; \qquad u_{4di} = (1 - a_{4i})u_a. \tag{1}$$

Likewise, the induction factor, b_4, for the bypass velocity at the static pressure equalisation point, u_{4b}, is defined relative to the reference velocity as:

$$u_{4b} = (1 + b_4)u_a. \tag{2}$$

Conservation of mass, momentum, and energy is considered in each of the annular streamtubes. At the rotor plane the i^{th} annular streamtube is at a radius r_i from the centre of rotation and has a radial thickness of δr_i (usually assumed to be uniform across the blade span), so that $\delta A_i \approx 2\pi r_i \delta r_i$. Conservation of mass requires:

$$\delta A_{1i} u_a = \delta A_i u_a (1 - a_{2i}) = \delta A_{4i} u_a (1 - a_{4i}), \tag{3}$$

where δA_{1i} and δA_{4i} are the cross-sectional areas of the i^{th} streamtube at stations one and four respectively. Conservation of energy is described upstream and downstream of the rotor plane and through the rotor bypass by the Bernoulli equation:

$$\begin{aligned} p_1 - p_{2i} &= \frac{1}{2}\rho u_a^2 (a_{2i}^2 - 2a_{2i}), \quad p_{3i} - p_4 \\ &= \frac{1}{2}\rho u_a^2 (a_{4i}^2 + 2(a_{2i} - a_{4i}) - a_{2i}^2), \quad p_1 - p_4 = \frac{1}{2}\rho u_a^2 (b_4^2 + 2b_4). \end{aligned} \tag{4}$$

Conservation of momentum in the i^{th} streamtube relates the thrust to the change in static pressure and momentum of the fluid:

$$p_1 \delta A_{1i} + p^* \delta A^* - p_4 \delta A_{4i} - \delta T_i = -\rho \delta A_i u_a^2 (1 - a_{2i}) a_{4i}, \tag{5}$$

where $p^* \delta A^*$ is the unknown streamwise force acting on the surface of streamtube as it expands between stations one and four. Following Nishino and Willden (2013), we assume slow expansion of the streamtube so that the unknown streamwise force may be accounted for with the approximation:

$$p_1 \delta A_{1i} + p^* \delta A^* = p_1 \delta A_i (1 - a_{2i}) + p^* \delta A^* \approx p_1 \delta A_{4i} = p_1 \delta A_i \frac{(1 - a_{2i})}{(1 - a_{4i})}, \tag{6}$$

i.e., the additional force contribution from the expanding streamtube is approximated as the increase in force that would result from the static pressure at station one being applied over the streamtube cross-sectional area at station four. Equations (3)–(5) are combined in the usual way as described in Garrett and Cummins (2007) to yield the following key results used in the following analysis. Using conservation of mass, the momentum equation (5) can be manipulated to yield the incremental thrust δT_i:

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