Incorporating Turbulent Inflow Conditions in a Blade Element Momentum Model of Tidal Stream Turbines

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ABSTRACT
Blade element momentum theory (BEMT) is a well-established method for evaluating the performance of turbines designed to extract energy from a flowing fluid. In this paper, we discuss a modified version of BEMT that allows for greater variation in the permissible inflow conditions, paying particular attention to inflow conditions that model turbulence in coastal waters in order to calculate the power output and other performance parameters of tidal stream turbines (TSTs). In the first part of the paper, we describe the modification we have made to standard BEMT analysis. In the second part, we describe how we create an appropriate representation of a turbulent tidal stream or marine current, and what parameters we can extract from measurements of a real current in order to create this representation. Some preliminary results are presented and their significance discussed.

KEY WORDS: Marine; turbine; renewable; energy; blade element momentum theory.

INTRODUCTION
The aim of this paper is to discuss some research carried out with the goal of predicting TST performance in turbulent marine currents. There have been many investigations of turbulence in the type of flows likely to be experienced by TSTs (see for instance Lueck and Lu, 1999; Lu et al., 2000; Trevethan and Chanson 2009), but one major difficulty in making these predictions is precisely that detailed measurements of the type described in these investigations are often not available for potential turbine installation sites. Thus, we seek to predict TST performance using not only data from real turbulent flows, but also from artificially created ‘synthetic’ turbulence which will satisfactorily predict the effects of real turbulence without first requiring a lengthy and possibly impractically expensive investigation of flow conditions.

As more and more computing power becomes available to a greater number of researchers, the number of fluid dynamics problems amenable to a computational solution is increasing. Nonetheless, many flows are still very expensive in terms of computational resources to simulate. One flow of interest for which this is true is that of a marine current turbine. Although there has been a quite successful attempt to simulate a turbine that extracts energy from a flow of water (see the work of O'Doherty et al. (2009)), this investigation was for a device at a smaller scale than real, installed TSTs would be, in order to make a direct comparison with experimental results from a flume; the upshot of this is that Reynolds number is much lower than would be the case in a full-scale device installed in a real tidal flow, which eases some of the difficulties of computation.

Although these investigations are very valuable, the difficulty and expense of performing such simulations puts them out of the reach of many developers of TSTs. Alternative tools that allow relatively rapid prediction of device performance are therefore of crucial importance in encouraging the proliferation and installation of marine current turbines. Such a tool is already well established, in the form of blade element momentum theory (BEMT).

CLASSICAL BEMT
BEMT was pioneered by Glauert (1948), who originally developed the theory in order to model aircraft propulsion using airscrews (i.e., propellers or tractors). It was later adapted to deal with devices that extract energy from a flow of air (i.e., wind turbines) rather than devices that expend energy to generate thrust, and more recently has been increasingly used to analyse TSTs (Orme 2006).

The basis of classical BEMT is the synthesis of two treatments of a turbine: firstly, as a porous actuator disc in a closed streamtube; secondly, as a collection of independent two-dimension aerofoils (or hydrofoils in the case of a TST). By equating the changes in axial and rotational momentum across the face of the actuator disc in the first treatment with the forces in the second, it is possible to derive a relationship between the gross flow velocities and the hydrodynamic forces that are developed at any particular radial station on the rotor blades. Integrating along the radius of the blades allows us then to calculate the resultant torque and power, and ultimately a selection of other parameters characterising the turbine’s performance.

The changes in axial and rotational momentum that occur in the streamtube are characterized by the axial and rotational induction factors, \( a \) and \( b \) respectively. \( a \) relates the axial velocity at the rotor disc, \( U_d \), to the freestream velocity \( U_\infty \) according to the following equation:

\[
U_d = U_\infty (1 - a) \quad (1)
\]

Similarly, \( b \) relates the swirl induced in the fluid by its passage through the rotor disc, \( \omega \), to the rotational velocity of the rotor, \( \Omega \):

\[
\omega = 2b\Omega \quad (2)
\]