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The Buhl correction factor applied to high induction conditions for tidal stream turbines

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ABSTRACT

Blade Element Momentum Theory (BEMT) is a computationally efficient method of calculating the performance of a tidal stream turbine (TST) generating energy from the ocean. This efficiency is achieved by making several simplifying assumptions; an unintended consequence of these assumptions is the omission of some phenomena that can significantly alter the performance and loads of a TST. We can ameliorate this by incorporating suitable corrections into a BEMT model, which allow us to account for some of the effects of these phenomena. This paper examines the implementation of corrections in an established BEMT solver for two such phenomena: tip/hub losses and high induction conditions.

Tip losses are attributable to the flow of fluid around end of the blade, a flow feature omitted in the classical BEMT treatment of turbines. At high tip speed ratios, above the designed operating range of the device, the theory based on an axial interference factor, *a*, diverges from experimental results and, indeed, becomes physically untenable. Buhl proposed a high induction correction factor for wind turbines operating in air and a modified version of his correction is implemented here for a TST operating in water. The tip/hub loss and high-induction corrections are well-integrated with one another. The validity of the high-induction correction is checked against experimental results; we find that our model predicts power output well but overpredicts axial thrust compared to laboratory observations.

1. Introduction

The development of turbine devices to capture renewable energy from flowing water over recent years has motivated the creation of new numerical models for these devices. These models are often based on experience from the wind turbine industry and range from the very simplistic to fully featured transient computational fluid dynamics with fluid structure coupling. Computationally intensive models based on 3D meshes can only be implemented for a few cases due to expense and time restraints; however, the experience of device designers indicates that the ability to analyse a wide range of the load cases experienced by such a device over its potential lifetime would be extremely useful. This motivates the development of a computationally inexpensive model capable of quickly obtaining results for a wide range of operating conditions.

Blade element momentum theory (BEMT) was chosen as a basis for the model described here due to its low computational demand and reasonable accuracy. Initially its application was marine and aviation propellers [1] but it was later applied to wind turbines and the approach is described in a number of wind turbine textbooks [2–5]. The central premise of BEMT is a combination of momentum flux and blade force analyses to derive equations for axial and torque forces at discrete blade elements. Two 'induction factors' for axial and rotational flow are introduced, which vary along the blade length and so must be calculated for each discrete blade element. The correct solution is found when we obtain values for the induction factors that bring the momentum flux and blade element analyses into agreement. Griffiths and Woollard [6] presented a clear approach to designing an optimally shaped wind turbine using BEMT, and Orme [7] has shown that this approach can be utilised for tidal turbine modelling. Determining appropriate values for the induction factors is typically solved by treating it as an optimisation or minimisation problem; converging to a suitable solution can be quite challenging, and has been addressed in a number of ways (see for instance Maniaci [8]). Masters et al. [9]

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presented a robust implementation of the method that is used as the basis of this work.

Due to the simplicity of its modelling approach, BEMT is known to experience certain difficulties in accurately predicting rotor performance when operating conditions differ significantly from the near-optimum case. One such condition is that of high induction: at high tip speed ratios (TSR) the axial induction factor can approach or exceed the theoretical upper limit of 0.5; this creates physical inconsistencies in the model, as the theory implies that the flow is reversed downstream of the turbine. In reality, the flow downstream slows and fluid is drawn in from outside of the rotating wake, increasing turbulence. This condition is thus also referred to as the turbulent wake state [4]. Validity limits of the BEMT and sketches of the behaviour of the streamlines can be seen in Fig. 1. Together with corrections for non-linear effects at the tip and hub, this paper focuses on a modification of the BEMT model to deal with high induction.

2. Model

2.1. Blade element momentum theory

A detailed account of BEMT can be found in most textbooks (see for instance [4,5]), so we present only a brief summary here, eliding most of the details. As mentioned above, BEMT synthesises two treatments of the turbine: as a rotor disc that alters the momentum flux in a streamtube, and as a collection of two-dimensional elements that approximate the turbine blades. The behaviour of the turbine in both these models is parametrised by two variables called the axial induction factor (denoted a) and the tangential induction factor (denoted b). The rotor disc model is partitioned into a series of annular elements and the blade model into a corresponding series of radial elements, allowing us to model variation in the turbine properties between the hub and tip. By equating the momentum fluxes through an annular element with the hydrodynamic forces on the matching radial element of the blades, we can determine suitable values for a and b. This is achieved through a minimisation. We first state the momentum flux predictions for the annular thrust dF_A and annular torque dT as

$$dF_{A1} = 4a(1-a)\rho U^2 \pi r dr \tag{1}$$

$$dT_1 = 4b(1-a)\rho U \Omega r^2 \pi r dr, \tag{2}$$

with Ω the turbine rotational velocity, U the freestream flow velocity, r the radial location of the annulus and dr its radial width. Similarly, we can express the same quantities in blade element terms as:

$$dF_{A2} = N\frac{1}{2}\rho V^2 c(C_L \cos\phi + C_D \sin\phi)dr \tag{3}$$

$$dT_2 = N\frac{1}{2}\rho V^2 cr(C_L \sin\phi - C_D \cos\phi)dr, \tag{4}$$

where N is the number of blades, V is the magnitude of the resultant velocity at the blade element, φ is the inflow angle (see Fig. 2) and C_L and C_D are the appropriate sectional lift and drag coefficients. Finally, we can obtain our a and b values for each radial station by defining an objective function g, given by

$$g = (dF_{A1} - dF_{A2})^2 + (dT_1 - dT_2)^2, \tag{5}$$

and then minimising g across a suitably-bounded (a,b)-space[9].

2.2. Tip losses

In BEMT, it is assumed that there is no flow along the span of the blade; in reality, however, the pressure differential between the suction and pressure sides of the blade will generate a vortex at the tip, producing a spanwise flow. This flow adversely affects aerodynamic efficiency near the tip, reducing lift and therefore torque and, ultimately, power production (Manwell [3]). Its omission from standard BEMT is a source of inaccuracy, and comparison of BEMT and CFD predictions by Madsen et al. [10] showed that standard BEMT has shortcomings in accuracy near the blade tip and root. The

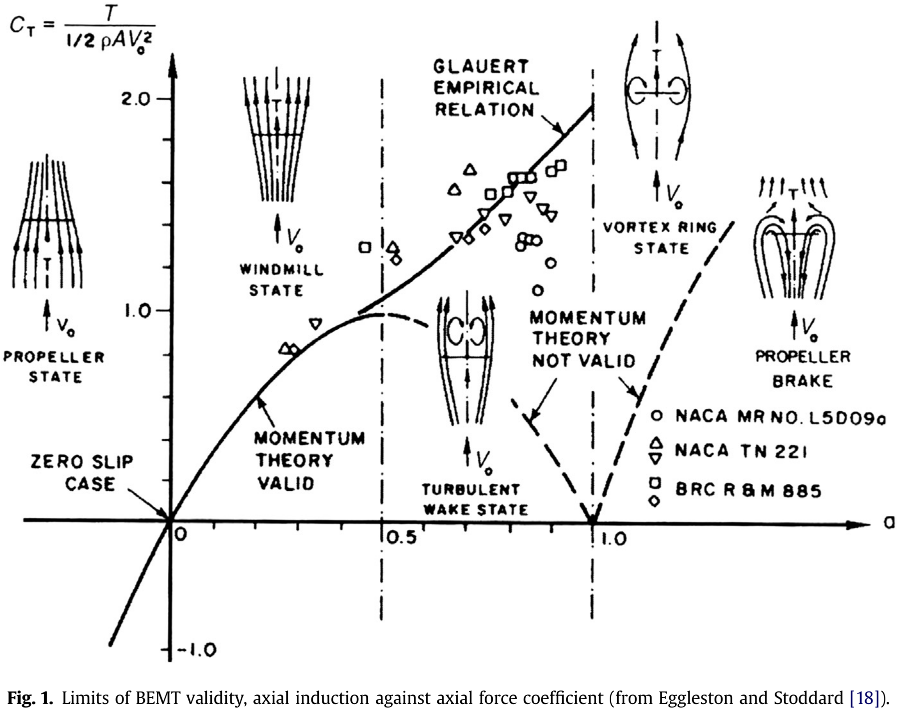

Fig. 1. Limits of BEMT validity, axial induction against axial force coefficient (from Eggleston and Stoddard [18]).