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Experimental study of the mean wake of a tidal stream rotor in a shallow turbulent flow

T. Stallard*, T. Feng, P.K. Stansby

School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M13 9PL, UK

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ABSTRACT

The mean wake of a three-bladed horizontal axis tidal stream turbine operating at maximum power coefficient has been investigated experimentally in a wide flume with width 11 times the depth, providing minimal restriction to transverse wake development and behaviour of large-scale horizontal turbulence structures. This is an important first stage for understanding wake interaction in turbine arrays and hence large-scale power generation. The rotor diameter has a typical value of 60% of the depth and the thrust coefficient is representative of a full-scale turbine. The shear layers originating from the rotor tip circumference show classic linear expansion downstream, with the rate of a plane shear layer vertically and 1.5 times that horizontally. These shear layers merge by around 2.5 diameters downstream forming a self-similar two-dimensional wake beyond eight diameters downstream with a virtual origin at two diameters downstream of the rotor plane. The spreading rate is somewhat less than that for solid bodies. The detailed velocity measurements made in the near wake show rotation and vorticity similar to that measured previously for wind and marine turbines although with asymmetry associated with bed and surface proximity. The longitudinal circulation in a transverse plane is conserved at about 1% of the swept circulation from the blade tip within two diameters downstream, the extent of detailed measurement. Turbines are usually designed using blade element momentum theory in which velocities at the rotor plane are characterised by axial and tangential induction factors and it is now possible to see how this idealisation relates to actual velocities. The axial induction factor corresponds to velocity deficits at 0.4–0.8 radii from the rotor axis across the near wake while the tangential induction factor at the rotor plane corresponds to velocities at 0.4–0.6 radii between 1–2 diameters downstream, indicating some general correspondence. For the two-dimensional self-similar far wake the two parameters defining the centreline velocity deficit and the transverse velocity profiles are likely to be insensitive to Reynolds number in turbulent conditions.

1. Introduction

Energy extracted from high velocity tidal flows by turbines is expected to make a significant contribution to electricity supply in many countries. We are here concerned with a three-bladed horizontal axis turbine which is the most common

* Corresponding author.
E-mail address: tim.stallard@manchester.ac.uk (T. Stallard).

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configuration, as it is for wind turbines. There have been many studies of power generation and thrust on marine and wind turbines both experimentally and numerically. Blade element momentum theory is a standard design tool for horizontal axis tidal turbines (Batten et al., 2008; Way and Collier, 2013). Design is determined by power output and the unsteady loading depends on the velocity and turbulence of the onset flow as well as the turbine operating conditions. For the anticipated large scale electricity generation by arrays of tidal turbines the onset flow to downstream turbines will be determined by the far wake of turbines located upstream. Here we undertake a laboratory study to investigate the mean far wake, and the upstream near-wake, of a representative tidal stream turbine at low blockage within a turbulent open channel flow.

The near wake has been modelled computationally, predicting time-averaged power and loading (e.g, McNaughton et al., 2014). Coherent tip vortices which break up downstream have been observed in LES (Large Eddy Simulation) studies (e.g. Afgan et al., 2013). Far field velocities due to a porous disc turbine representation have been measured by Myers and Bahaj (2010) and due to model turbines by Maganga et al. (2010) with low blockage; they both showed that increasing upstream turbulence increased wake recovery, but the resulting mean flow was not categorised. Chamorro et al. (2013) investigated the effect of upstream turbulence on turbine response and its effect on wake recovery. Response was coupled to upstream turbulence below a critical rotation frequency and uncoupled at higher frequencies. Wake recovery was linked to the large scale motions in the flow resulting from the tip vortices. There have been many more studies of wind turbine wakes (e.g. Vermeer et al., 2003) which relate directly. These include computational studies (e.g. Wu and Porte-Agel, 2011), field trials (Högstrom et al., 1988; Magnusson and Smedman, 1999) and experimental laboratory studies, typically at small geometric scale with reduced thrust coefficient (Hu et al., 2011; Zhang et al., 2012). These show the importance of upstream turbulence in enhancing wake recovery which is generally more significant than shear effects. Various wake details have been analysed including tip vortex generation and breakdown and large scale wake meandering. An important difference for tidal turbines is that the wake is constrained vertically by a water (free) surface which is particularly likely to influence the far wake. It is well known that the turbulence structure of such shallow flows is anisotropic with horizontal length scales many times the vertical (e.g. field measurements of Thomson et al. (2012) and inferred from modelling by Stansby (2003)). This could also be a limitation for the study of Chamorro et al. (2013) where the streamwise length scale was 1.4 times the depth and both the horizontal structures and the far wake could be influenced by the channel width of 2.4 times the depth.

In this study we investigate the near and far wake in a wide flume with width more than 10 times the depth so that horizontal turbulence and far wake will not be significantly influenced by the side walls. We are concerned with the mean flow characteristics and how the relatively unconstrained, and nearly axisymmetric, near wake merges into the depth-constrained far wake. The turbine diameter is about 60% of the water depth and the turbine operates at maximum efficiency, at the tip speed ratio for maximum power coefficient for this geometric scale. The rotor is designed such that the thrust coefficient is typical of a full-scale turbine. Since the blade element momentum theory is a standard design tool based on axial induction and tangential induction factors we relate the values resulting from this rotor design to the physical wake.

The paper is organised as follows: Section 2 Experimental Arrangement, Section 3 Wake Velocity Deficit, Section 4 Near Wake Rotation, Section 5 Wake Turbulence and Section 6 Conclusions.

2. Experimental arrangement

Measurements were made of the wake generated downstream of a single turbine of diameter $D=0.27$ m located at mid-depth in an open channel flow of width $W=5$ m, depth $h=0.45$ m and with mean velocity $U_0=0.46$ m/s. The longitudinal, vertical and transverse axes are denoted as x, z and y. The global blockage based on swept area to channel cross section (A_D/Wh) is therefore 2.5% and wake expansion is effectively unconstrained in the transverse direction with $W=18.5D$, but is constrained vertically by the bed and free-surface as $h=1.67D$. The locations (X, Y, Z) reported herein are relative to the rotor origin located at $x_0=13.3h$ from the flume inlet. Some further details on this arrangement, including a schematic of the flume, are given by Stallard et al. (2013). A 3-bladed rotor is employed as a likely form of rotor for widespread deployment in large farms. Horizontal thrust, applied torque and rotational speed of the rotor were recorded.

2.1. Flow velocity measurement

Time varying velocities were measured using a NORTEK Vectrino+ ADV with velocity range ± 1 m/s, sample volume dimension of 3 mm and transmit length of 8.7 mm (Nortek, 2006). Three components of velocity were recorded, u_x, u_y, u_z. The probe was positioned in a vertical $y-z$ plane downstream of the rotor using an automated traversing system with position accurate to less than 1 mm. Signal to noise ratio (SNR) and correlation coefficient (COR) tested prior to each set of measurements indicate that the majority of samples ($>95\%$) have SNR >15 dB and COR $>90\%$. At each co-ordinate a 60 s sample was recorded at 200 Hz. This provides resolution into the turbulence subrange (frequency 32 Hz based on channel flow velocity, see p. 30 Nezu and Nakagawa, 1993) and was found to be sufficient for time-averaged values of velocity, denoted U, and of longitudinal turbulence intensity (u'_x/U_0 where u'_x is the rms of fluctuating longitudinal velocity) to be calculated to within 2% and for turbulence length scales to be converged to within 5%.

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