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A large scale model experimental study of a tidal turbine in uniform steady flow

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ABSTRACT

An experimental study measuring the performance and wake characteristics of a 1:10th scale horizontal axis turbine in steady uniform flow conditions is presented in this paper.

Large scale towing tests conducted in a lake were devised to model the performance of the tidal turbine and measure the wake produced. As a simplification of the marine environment, towing the turbine in a lake provides approximately steady, uniform inflow conditions. A 16 m long × 6 m wide catamaran was constructed for the test programme. This doubled as a towing rig and flow measurement platform, providing a fixed frame of reference for measurements in the wake of a horizontal axis tidal turbine. Velocity mapping was conducted using Acoustic Doppler Velocimeters.

The results indicate varying the inflow speed yielded little difference in the efficiency of the turbine or the wake velocity deficit characteristics provided the same tip speed ratio is used. Increasing the inflow velocity from 0.9 m/s to 1.2 m/s influenced the turbulent wake characteristics more markedly. The results also demonstrate that the flow field in the wake of a horizontal axis tidal turbine is strongly affected by the turbine support structure.

1. Introduction

The tidal energy industry is reaching commercial status following an increase in the deployment of prototype tidal energy converters (TEC) in recent years. Once tidal technologies have been demonstrated through prototype testing, the installation of multiple devices in arrays is expected to follow. In order to identify the optimum layout of an array, knowledge of the wake generated by a TEC device is required. Using information about the wake of an upstream device, developers can make a more informed judgement on initial array layouts.

The tidal flow regime is complex with a number of contributory factors resulting in an unsteady, non-uniform flow that includes varying scales of turbulence. Some contributions to variable flow generation at tidal sites include the local bathymetry, seabed roughness and turbulence generated by wind and swell-induced waves (Boake et al., 2009; Myers and Bahaj, 2008). When a tidal device is deployed in a high energy tidal site it adds to the factors affecting the flow. The device support structure and rotating turbine both generate turbulence, but the scale and intensity of turbulence generated at full scale has had minimal coverage in publications at present. Information relating to the combination of all the contributing turbulent flow fields will become more important when tidal energy devices are deployed in arrays, as the flow field in the wake of a device will affect the inflow conditions for turbines located downstream.

The exact form of the wake created by a TEC may be device-specific, but the fundamental wake characteristic can be decomposed into two distinct regions: a near wake and a far wake region (Lissaman, 1979). The near wake region is located directly behind a turbine, where coherent turbulent structures generated from the turbine can be detected. The difference in velocity between the slower-moving fluid in the wake and the free stream flow produces a shear layer along the wake boundary. In the shear layer eddies are formed, which help to mix the lower velocity fluid in the wake with the higher velocity fluid surrounding the wake. This mixing process transfers momentum into the wake and increases the flow velocity. The distance downstream where the shear layer becomes thick enough to meet the turbine wake axis is used to mark the end of the near wake region and the start of the far wake. In wind turbine wake studies this transition point has been detected between two to five rotor diameters downstream of the turbine (Vermeer et al., 2003).

In the far wake, turbulent mixing gradually decomposes the wake and through entrainment with the surrounding flow increases the size of the wake. The ambient turbulence conditions have been shown to influence the rate of recovery of the wake

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velocity with downstream distance (Mycek et al., 2014). Similarly Medici and Alfredsson (2005) measured the influence of the free-stream turbulence on the wake recovery of a wind turbine. The results show that the initial reduction in velocity was similar for both cases, but with distance from the turbine (approximately three rotor diameters downstream) the recovery of the wake velocity was enhanced due to higher ambient turbulence levels.

Far wake characteristics may be considered most useful for inter-device spacing within an array. However, decisions on inter-array spacing may also benefit from an increased understanding of the near wake and information about fluid–structure interactions around a TEC. Near wake studies are particularly beneficial to investigate any influence the turbine (and support structure) geometry may have on the wake characteristics, specifically any measureable coherent turbulent structures (Afgan et al., 2013; Chamorro et al., 2013) and the combined influence of the turbine and support structure (Myers and Bahaj, 2009). Following a comparison between numerical modelling methods, and using the experimental results from Chamorro et al. (2013), Kang et al. (2014) concluded that due to the apparent link between the wake meandering mechanism and the hub vortex structure, the consideration of the geometry of the turbine near the hub region was critical (for the turbine studied) to accurately resolve the mean flow and dynamic characteristics of the far wake. Near wake experimental studies also support identification of the beginning of the far wake region (i.e. a self-similar two-dimensional wake) downstream of a device (Stallard et al., 2015).

The majority of flow field studies around tidal turbines have been carried out in the laboratory (e.g. Good et al., 2011; Rose et al., 2011; Stallard et al., 2015) or at small scale in the field (Birjandi et al., 2012; Sun, 2008). Porous discs have been used in small scale investigations to study the far wake characteristics of horizontal axis turbines on the assumption that the far wake characteristics are similar to a full scale rotor if the thrust on the rotor and channel properties are correctly scaled (Harrison et al., 2008; Myers and Bahaj, 2010). A summary of published tidal stream turbine wake studies can be found in Tedds et al. (2014).

Porous discs have also been used for wind turbine wake studies in the laboratory (Builjtes, 1978; Sforza et al., 1981). However, there are some principle differences between a porous disc and a rotor which make it unsuitable for near wake studies, namely there is no mechanical power generated by the flow and vortices shed from a disc differ from those from a turbine. Using a rotor to model horizontal axis turbines at smaller scales incurs scaling issues as described by Myers and Bahaj (2010). Another factor which must be taken into account is the blockage ratio between the channel and rotor cross sectional areas. Single prototype tidal stream turbines in a full scale environment operate in a relatively unconstrained flow and a low blockage ratio in laboratory tests should be maintained to reflect these conditions at full scale. It has been shown by Whelan et al. (2009) that a high blockage effect in a channel could significantly increase the amount of power extracted from the flow by a single turbine. Conducting larger scale model experiments using a rotor permits a more representative study of the flow field in the near wake. Taking into consideration scaling and blockage effects, Myers and Bahaj (2009) chose a rotor diameter of 0.8 m (considered to be 1:20th scale) to conduct experiments in the near wake of a tidal turbine.

Experiments carried out in the laboratory provide controlled test conditions, with a high degree of accuracy, repeatability and a greater coverage of the wake can be obtained more readily at smaller scales. Large scale field tests are inherently more uncontrollable and difficult to conduct than laboratory experiments, but can provide a valuable step in the development of commercial tidal devices. The motivation for the towing tests presented was to simplify the operating conditions to which a large scale turbine model would be exposed at a nursery site in Strangford Lough. The approach was adopted following initial sea trials of the Evopod model highlighted the difficulties of isolating wake characteristics in the highly variable test environment. Carrying out towing tests, as a precursor to large scale sea trials, provides the potential to characterise the model performance and wake generated (under steady uniform conditions) which may prove valuable in the interpretation of data gathered during the sea trials. Finlay and Bryden (2011) discuss the challenges of establishing field tests of scale models in Strangford Lough. The experimental approach presented by the authors is based on the initial work described in this paper. The large scale towing tests also provide the opportunity to test the functionality of a model and ensure all device components are working correctly before deploying the device in a less accessible tidal environment.

The large scale towing tests were conducted as part of the SuperGen Marine Energy Research Consortium Phase 2 (SuperGen Marine, 2012) to contribute to the understanding of the hydrodynamic performance of a tidal turbine. This included the estimation of the interaction of the turbine with the incoming steady, uniform flow and the subsequent wake generated. Understanding the processes associated with a single tidal turbine in steady uniform inflow conditions can be seen as the first step to understanding the interaction between multiple turbines.

In this study, model performance tests and wake flow characterisation of a 1:10th scale horizontal axis tidal turbine (rotor diameter of 1.5 m) were conducted at a large towing test facility, which was specifically designed for the experimental campaign by the authors. As a simplification of the marine environment, the lake provides in principle steady, uniform flow conditions to a tidal turbine towed through the water. An assumption made within the scope of the towing test is that the wake results will be reflective of a tidal device operating in moving water. In towing tests momentum is introduced into the wake by the vessel and the rotating turbine, therefore the flow velocity measured in the wake is relative to the towing platform, as opposed to the absolute flow velocity measured in the wake of a device in a channel of moving water. Results from previous wake measurement campaigns, carried out by Sun (2008), showed that although the real operating condition for a tidal turbine is water moving past a device, similar wake results were obtained when the same device (a 250 mm porous disc) was tested in a towing tank and a moving water channel.

This paper describes the large scale towing test facility designed and constructed for model performance and near wake flow field studies. An experimental campaign using the 1:10th scale Evopod horizontal axis tidal turbine device developed by Oceanflow Energy Limited is detailed. Model performance and near wake characteristics results are presented for varying inflow conditions.

2. Methodology

Forward motion at uniform speed through the lake environment provides an approximation to steady uniform inflow conditions, achieved when towing the model through a body of still water. These experiments allowed the change in steady uniform flow conditions due to the presence of the tidal device to be quantified, before adding the complexity of the unsteady non-uniform inflow conditions which are typically in tidal flow. The towing experiment described here was planned as a precursor to carrying out tests at a large scale model test site in Strangford Lough, Northern Ireland. The selection criteria for the test site were based on a full scale peak flow of 3 m/s and 60 m water depth. At 1:10th scale this is equivalent to a peak flow of 0.95 m/s and a 6 m water depth.