Renewable and Sustainable Energy Reviews 56 (2016) 851–864

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# The characterisation of the hydrodynamic loads on tidal turbines due to turbulence

I.A. Milne [a,*], A.H. Day [b], R.N. Sharma [a], R.G.J. Flay [a]

[a] Department of Mechanical Engineering, The University of Auckland, Private Bag 92019, Auckland Mail Centre, Auckland 1142, New Zealand
[b] Department of Naval Architecture and Marine Engineering, University of Strathclyde, Henry Dyer Building, 100 Montrose Street, Glasgow G4 0LZ, UK

ARTICLE INFO

*Article history:*
Received 5 March 2015
Received in revised form
21 November 2015
Accepted 30 November 2015

*Keywords:*
Tidal turbine
Turbulence
Unsteady hydrodynamics
Model-scale testing

ABSTRACT

An improved characterisation of the hydrodynamic blade loads due to onset turbulence is essential in order to mitigate premature failures, reduce excessive levels of conservativeness and ultimately ensure the commercial viability of tidal turbines. The literature focussing on the turbulence in fast flowing tidal streams and of the unsteady loads that are subsequently imparted to rotors has previously been very limited. However, increased activity in the tidal energy community has led to new investigations and insights which are reported in this paper.

It has been found that through the use of acoustic Doppler-based sensors, the streamwise turbulence intensities generally tend to a value of approximately 6–8% at the mid-depth of proposed tidal energy sites. Evidence that the anisotropic structure and scales of the turbulence are more consistent with open-channel-based models than atmospheric-based correlations has also been found. Rapid distortion theory has been applied to estimate that the standard deviation of the streamwise turbulent velocity fluctuations in the onset free-stream flow may be amplified significantly by 15% due to the presence of a turbine. The turbulent fluctuations have also been predicted to remain well correlated over the outer span of the blades at the rotational frequency of the rotor.

Recent model-scale experiments have enabled the unsteady hydrodynamic loading to be isolated from the steady-flow loading. For cases where the boundary layer remains primarily attached across the blades, this has enabled linear transfer functions to be developed and applied to model the response to a multi-frequency forcing. It has also been found that phenomena consistent with delayed separation and dynamic stall can result in a blade root bending moment that exceeds the steady value by 25%, and this needs to be taken into account in design to reduce the probability of failure.



**Contents**



* Corresponding author. Tel.: +64 9 373 7599x88146; fax: +64 9 373 7479.
*E-mail addresses:* imil015@aucklanduni.ac.nz (I.A. Milne), sandy.day@strath.ac.uk (A.H. Day), r.sharma@auckland.ac.nz (R.N. Sharma), r.flay@auckland.ac.nz (R.G.J. Flay).

http://dx.doi.org/10.1016/j.rser.2015.11.095
1364-0321/

## 1. Introduction

If tidal stream energy is to be competitive with other forms of energy generation, tidal turbines must be economical to manufacture and operate reliably over their design life of at least 20 years [1,2]. Reliability is particularly critical for turbines which are deployed in more remote communities. In these locations, replacement components and expertise are not likely to be readily available and electricity supply would be jeopardized by failure [3]. This is however complicated by the harsh and unforgiving environment in which tidal turbines must operate.

There are now several examples of early-generation turbines that have experienced catastrophic failures. This has been attributed to underestimating the magnitudes and the spectral characteristics of the hydrodynamic loads [4]. Furthermore, only draft industrial guidelines exist for accounting for both the turbulence and unsteady loads on tidal turbines [1]. These guidelines incorporate empirical models and theories that were devised primarily for wind turbines and which have not been extensively validated for tidal turbines. In an attempt to mitigate potential failure, designers of tidal turbines have resorted to incorporating excessive safety factors in fatigue load predictions which has subsequently increased the cost of the turbines [5,6].

In order to gain confidence in the predictions of the hydrodynamic loading, prevent unexpected failures and ultimately improve the economics of tidal turbines, the industry faces a number of significant issues and challenges. Firstly, compared to the mean flow, there is paucity of data available on the turbulence characteristics in strong tidal flows. This is indicative of the inherent technical difficulties in acquiring measurements of turbulence in fast flowing currents and the relative infancy of the tidal stream turbine industry [7]. Appropriate strategies to obtain measurements of the turbulent flow at tidal energy sites must therefore be devised. These should allow for not only the magnitudes of the turbulence to be observed, but also the structure and dominant scales which are crucial for informing the rotor loading [8].

It is also important to consider that the turbulence that is onset to a turbine and which induces the unsteady loading may differ to that which is observed in an undisturbed flow. In particular, the strain imparted on the flow field due to the extraction of momentum may distort the turbulence. Furthermore, a turbine blade rotates through a non-coherent turbulent field and may encounter an eddy multiple times. This can effectively give rise to a forcing spectrum dissimilar to that which would be measured at a fixed point. Therefore, appropriate techniques must be developed to quantify these effects in order to define the unsteady velocity that is incident on a rotor blade.

The unsteady loads which are subsequently induced from this turbulent flow comprise a complex interaction of both unsteady non-circulatory and circulatory effects, the latter commonly associated with dynamic inflow. For turbines operating near peak power, additional circulatory contributions from delayed separation and dynamic stall of the blades can also be present. Comprehensive discussions on these effects in the context of helicopter rotors and wind turbines are provided by Peters et al. [9] and Leishman [10], for instance. Together, these frequency dependent effects can give rise to overshoots in the load magnitudes over the equivalent value that would be measured in steady flow, as well as hysteresis in the response. Their significance may also be comparably greater for tidal turbines compared to wind turbines, due to the higher fluid-to-structural density ratio [11], reinforcing the need for their quantification.

While numerous studies have characterised the hydrodynamic loads on tidal turbines for steady flow (see, for instance, [12,13]), studies for unsteady flow conditions have been limited. Such test data are necessary to quantify the significance of the unsteady hydrodynamic loading contributions, verify numerical models and ultimately develop design guidelines to account for unsteadiness. The lack of test data on unsteady loading is arguably attributed to the substantial cost of using large, high quality facilities which are required to account for the effects of scaling and to reduce the effects of blockage. This calls for appropriate methodologies to be developed to enable the underlying hydrodynamic phenomena and their complex interactions to be quantified. Obtaining measurements of the out-of-plane (thrust-wise) hydrodynamic loading is of utmost importance as it is this component which typically governs the total structural loading on a horizontal-axis tidal turbine [14,15].

## 2. Objectives

Drawing on these challenges, the primary aim of this paper is to present and discuss recent advances that have been made on the characterisation of turbulence at tidal energy sites and the hydrodynamic loading on tidal turbines. The issues addressed in this review have drawn significant interest recently, spanning across both academia and industry and in many instances involving joint industry partnerships.

Specifically, the experimental techniques which have been adopted by researchers to measure turbulence are discussed and observations of turbulence in fast flowing tidal streams are collated. This is followed by a description of the application of theoretical models to account for the amplification and rotational sampling of the turbulent eddies necessary to obtain the forcing imposed on a turbine. Methodologies for experimentally testing tidal turbines in unsteady conditions at model-scale are then critically reviewed. Finally, the underlying unsteady hydrodynamic phenomena acting on a rotor are discussed in view of the recent experimental measurements that have become available.

## 3. Observations of turbulence at tidal energy sites

### 3.1. Measurement strategies

Experimental studies from circa 1960s provided initial insights into the characteristics of the turbulence in the seabed boundary layer of tidal flows. Grant et al. [7] utilised hot film and electro-current techniques to observe the turbulence spectra at high wavenumbers ($k_x = \pi f / U > 1$, where $f$ is the temporal frequency