Renewable Energy 77 (2015) 338–350

Contents lists available at ScienceDirect

Renewable Energy

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

Blade loading on tidal turbines for uniform unsteady flow

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 22 January 2014
Accepted 10 December 2014
Available online

Keywords:
Unsteady hydrodynamics
Tidal turbine
Dynamic inflow
Added mass
Towing tank testing

ABSTRACT

An improved characterisation of the unsteady hydrodynamic loads on tidal turbine blades is necessary to enable more reliable predictions of their fatigue life and to avoid premature failures. To this end, this paper presents a set of blade-root bending moment responses for a scale-model tidal turbine subjected to an unsteady planar forcing in a towing tank. In cases where the boundary layer was believed to be attached to the outer sections of the blade, the out-of-plane bending moment amplitude for unsteady flow was up to 15% greater than the corresponding load measured in steady flow and exhibited a phase-lead of up to 4.5°. Both these observations are qualitatively consistent with the effects of dynamic inflow and non-circulatory forcing. The bending moment responses for a forcing time history that comprised multiple frequencies, as well as for a discrete half-sinusoidal perturbation, were able to be reconstructed reasonably well using the responses obtained from single-frequency oscillatory flows. This suggests that blade designers could utilise relatively low fidelity techniques and conduct potentially fewer experimental tests to acquire the fatigue load spectrum.

1. Introduction

If tidal stream energy is to prove competitive with other forms of energy generation, tidal turbines must be economical to manufacture and also operate reliably over their design life of 20 years or more [9,25]. Reliability is arguably an even greater concern for turbines which are deployed in remote communities, where replacement components and expertise are not likely to be readily available and electricity supply could be jeopardised [1].

The turbulent flow which is onset to the turbine presents a significant technical challenge for designers. Failures of early generation tidal turbines have been cited to be a consequence of a poor understanding of the magnitudes and the spectral characteristics of the resulting hydrodynamic loads [13]. Compounding the issue is that questionable assumptions and safety factors are widely used in predicting the unsteady loads of tidal turbine blades [9,26].

This can be attributed, in part, to a lack of experimental data on the unsteady hydrodynamic loading on tidal turbines for a forcing that is representative of the unsteady flow. This data is necessary to understand the underlying phenomena which are present, to quantify the loading and subsequently, to ascertain the level of complexity that is required for modelling the loads and predicting fatigue life.

It is important to also consider that similar issues are faced by designers of hydro-kinetic turbines which are deployed in rivers and canals [10]. Therefore, providing an improved characterisation of the unsteady blade loads is expected to draw wide interest.

2. Literature review

2.1. Unsteady loading of rotors

The unsteady hydrodynamic loads of a rotor that is subjected to an axial flow perturbation include both circulatory and non-circulatory components. Provided that the boundary layer remains attached to the foil at the outer sections of the blade, the unsteady circulatory forces are attributed to the vorticity that is shed from the blade and then trailed in the wake. For perturbations with frequencies relatively small in comparison to the rotational frequency of the rotor, the circulatory loading is commonly associated with dynamic inflow. These circulatory effects were first observed for helicopter rotors in the 1960s and have been discussed by researchers such as [17] and [12].

The dynamic inflow phenomenon can be attributed to the induced flow in the trailed wake taking time to reach a new equilibrium state

* Corresponding author. Tel.: +64 9 373 7599; 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.renene.2014.12.028
0960-1481/

Nomenclature

λ	tip-speed ratio, $\Omega R/U$
μ	current number, $\tilde{u}/U$
Ω	rotational speed of rotor (rad s^{-1})
$\tilde{u}$	maximum oscillatory carriage velocity (m s^{-1})
A	swept area of rotor (m^2)
C_M	blade-root bending moment coefficient for steady-flow, $M/½\rho U^2AR$
C_P	power coefficient, $P/½\rho U^3A$
C_T	thrust coefficient, $F_x/1/2\rho U^2A$
f	oscillatory frequency of carriage (Hz)
F_x	axial (thrust) force on rotor shaft (N)
k	reduced frequency, $\pi cf/\Omega r$
k_{M_y}	out-of-plane blade-root bending moment coefficient normalised by the tip-speed, $M_y/½\rho(\Omega R)^2AR$
m	frequency ratio, $2\pi f/\Omega$
M_x	blade-root in-plane bending moment (N m)
M_y	blade-root out-of-plane (thrust-wise) bending moment (N m)
n_s	sampling frequency (Hz)
R	radius of rotor tip from hub centre (m)
U	steady carriage speed (m s^{-1})
M_{yQS}	blade-root out-of-plane bending moment measured in steady-flow at the equivalent instantaneous velocity and rotor speed (N m)
$\overline{M_y}_{QS}$	blade-root out-of-plane bending moment measured in steady-flow at the mean tip-speed ratio (N m)

following a change in loading at the rotor plane. The lag in the induced velocity response effectively gives rise to a phase-lead in the incident velocity at the blade section relative to the axial velocity in the free-stream [23]. This subsequently also results in a phase-lead and overshoot in the bending moment response of the blades, relative to the quasi-steady loading.

The non-circulatory loads arise due to the pressure forces which are required to accelerate the fluid in the vicinity of the blade [11]. This forcing is independent of the presence of the rotor wake and acts 180° out-of-phase with acceleration. For a perturbation in the axial velocity, this implies that the non-circulatory forcing also gives rise to a phase-lead in the loading over the velocity.

Whilst the unsteady loads of wind turbines subject to an axial forcing have been investigated and found to be relatively small [20], they have been seldom reported for tidal turbines. In fact, [23] argued that the effects of an axial velocity perturbation may be comparatively more significant for tidal turbines than for helicopter rotors or wind turbines. This is owing to the ratio of the fluid to structural density being much closer to 1 than for rotors in air. This reinforces the need to quantify its contribution.

2.2. *Experimental investigations of unsteady tidal turbine loading at model-scale*

A variety of techniques have been employed to study the unsteady loading of horizontal-axis tidal turbines in the laboratory. Ref. [14] acquired measurements of the mean thrust on the tower structure of a 700 mm diameter (approximately 1/30th scale) tidal-turbine in a flume, where the turbulence intensity in the flow was varied from 8% to 25%. However, the spectral characteristics of the turbulence were not reported, and it is difficult to relate these results to a full-scale turbine. Furthermore, the perturbations in the thrust were not reported and it cannot be ascertained whether any overshoots in the loading were present.

Ref. [3] reported on experiments of a model tidal turbine towed at constant velocity in a still-water tank, where the unsteady flow was instead imparted from surface waves. Unlike other wave-based experiments, such as those of [8]; the blade-root bending moment was specifically measured. Acquiring the bending moment response from individual blades is deemed to be more suitable for quantifying the unsteady loading. This is because the non-coherent loading imparted by the surface waves would not be uniform over all three blades and could therefore only be determined in an averaged sense from thrust measurements from the shaft or support structure. Furthermore, additional losses through the shaft bearings etc. do not have to be accounted for if blade root bending moments are measured directly.

For relatively low frequency and small amplitude surface waves, Ref. [3] found that the bending moment response compared reasonably well with a prediction using a quasi-steady numerical blade element-momentum model with no acceleration effects included. This implies that the unsteady hydrodynamic contribution for these cases was relatively small. However, establishing the contribution from the non-circulatory and circulatory forcing is difficult, owing to the need to estimate the kinematics of the flow using measurements of the water surface elevation in conjunction with a linear wave theory. Additionally, inferring relatively small phase differences from measurements of the free surface to quantify the unsteady loading is particularly challenging.

The study by Ref. [23] involved perturbing a 300 (mm) diameter twin-bladed rotor using a towing carriage. These experiments were conducted in a flume with a steady flow and the total axial thrust was inferred from the force applied to the fixed structure that supported the rotor. It was the first investigation that attempted to establish the relative contribution of the forcing components in-phase and out-of-phase with velocity of a tidal turbine. However, as the quasi-steady loading would also appear in-phase with velocity and was not removed, quantifying the unsteady hydrodynamic contribution alone from these results is inherently complicated.

Whilst the investigation by Ref. [23] showed promise, the experimental set-up was subject to not only the challenges of speed control, high blockage and background unsteadiness, but also to the presence of a low frequency wave. These issues restricted the maximum oscillatory frequency that was able to be investigated to approximately $f = 0.1$ Hz. This corresponded to a reduced frequency limit at the radial location of $r = 0.75R$, where R is the rotor radius, of approximately $k = \pi fc/\Omega r = 0.02$, where c is the local chord and Ω is the rotational speed of the rotor. As discussed by Ref. [15]; these reduced frequencies are up to 6 times smaller than could be imparted by turbulence due to the effect of rotational sampling and are considered to be representative of large eddies. Therefore, it is possible that the effects of unsteadiness on the loads were inherently small at these relatively low frequencies.

In an attempt to overcome some of these shortcomings, the investigation of Ref. [16] adopted the approach of superimposing an unsteady surging motion upon a steady forward speed in calm water in a towing tank. A tri-bladed turbine was used in the study, where the blockage was relatively low at approximately 5%, the rotor speed was maintained constant and the blade-root bending moments were measured. The study demonstrated that for a turbine perturbed about a tip-speed ratio near maximum power, the unsteady bending moments can be significant and 25% greater than the maximum load under steady flow. However, these large loads, which were also non-linear, were believed to be affected by separation of the boundary layer on the foil and dynamic stall. This complicated the identification and quantification of the contribution to the loads from the unsteady attached flow phenomena.