International Journal of Marine Energy 16 (2016) 51–64

Contents lists available at ScienceDirect

International Journal of Marine Energy

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

A sensitivity analysis on tidal stream turbine loads caused by operational, geometric design and inflow parameters

T.M. Nevalainen *, C.M. Johnstone, A.D. Grant

Energy Systems Research Unit, Mechanical & Aerospace Engineering Dept., University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, UK

ARTICLE INFO

Article history:
Received 12 February 2016
Revised 19 April 2016
Accepted 9 May 2016
Available online 10 May 2016

Keywords:
BEMT
Sensitivity analysis
Tidal stream turbine
Structural loading
Hydrodynamics
Shaft loading

ABSTRACT

This paper presents a sensitivity analysis on a numerical tidal stream turbine model where a multitude of input parameters' effect on the load output were determined. The statistical procedure used, known as the Morris method, provided insight into the interactions between the parameters as well as showing their comparative influence on the turbine loading. The investigation covered parameters from the operational, geometric design and inflow variable domains where the rotor radius, current shear, blade root pitch, surface velocity and wave height were identified as most influential. The blade pitch was regarded as a surprisingly prominent influence on the loads. The turbine's operating depth and the blade geometry were also found to be of limited influence in the ranges investigated. In terms of load transmission into the internal components of a turbine's drive train, the rotor out-of-plane bending moment, or eccentric bending moment, was found to be a considerable contribution to the off-axis loads on the shaft. Therefore, special attention was paid to the input parameters' relationship to the eccentric load component by performing a detailed study on the load variations caused by the identified primary input parameters. It is concluded that performing a sensitivity analysis on a tidal stream turbine in a specific operating climate can yield insight to the expected load range and that the eccentric loading transmitted to the shaft is significant for most input cases.

1. Introduction

As the development of tidal stream turbines (TSTs) draws ever closer to the deployment of full scale arrays, such as the MeyGen project off the north coast of Scotland [1], the cost and durability of the individual turbine units will be an important factor if the industry is to gain commercial acceptance.

It is reasonable to believe that TSTs will be highly susceptible to component fatigue failures due to the cyclic stresses brought on by the variations the in inflow velocity in the marine environment [2–4]. Furthermore, it is suspected that the non-uniform inflow velocity gradient across a turbine's rotor will cause off-axis, or eccentric, bending moments on the shaft connection which may be translated into the drivetrain causing excessive wear on internal components such as bearings and seals [3].

Many studies have been presented using both experimental [5–7] and modelling approaches [8,4,9] to investigate the hydrodynamic loads on TSTs caused by a variety of sources such as waves, currents, yaw-misalignment and turbulence.

* Corresponding author.
E-mail address: thomas.nevalainen@strath.ac.uk (T.M. Nevalainen).

http://dx.doi.org/10.1016/j.ijome.2016.05.005
2214-1669/

The measured quantities of most investigations have been the axial shaft thrust, shaft torque and blade root bending moments, typically collected for one single turbine design. Due to the inherent complexity of the physical problem of hydrodynamic loads on TSTs, experimental data-sets are usually limited to the variation of only a few parameters. Consequently, there are currently few studies available highlighting what parameters are most influential on turbine load generation globally and there is a lack of standardised comparative methods to determine the relative importance of each of the input parameters [10].

Galloway et al. [11] showed that the maximum load fluctuations for a scale model TST were 175% of the median for the out-of-plane bending moments, and the corresponding in-plane load variations were 100% of the median. The study showed that the out-of-plane loading was as much as 9.5 times greater than the in-plane loads and the cyclic loading from the wave action was reported to be a likely source of accelerated fatigue.

The magnitude and variational characteristics of the out-of-plane bending moments applied to the drive shaft of a TST were studied by Tatum et al. [3], who used a CFD and fluid structure interaction approach to present blade and rotor loading time-histories. The results for a turbine operating in a sheared current flow showed a variation in the resultant rotor out-of-plane bending moment of 24 kNm caused by the non-uniform loads over the blades, which would ultimately be transmitted into the drive train. It was also reported that the angular direction of this bending moment had a range as high as 67°, which was speculated to lead to the load being applied over a limited area of the drivetrain seals and bearings, resulting in reduced life expectancy.

Furthermore, a local parameter study on TST loads was presented by Milne et al. [12] in order to quantify the relative importance of the different inflow parameters on the blade loads of a device. The parameters investigated were the mean current speed, shear profile, water depth, hub height, wave height, wave period and turbulence intensity. The study was conducted using a numerical model of a full scale turbine using a commercial Blade Element Momentum Theory (BEMT) package [13]. The study showed that for the parameters investigated, the wave height and period had a dominant influence on the blade loads, whilst the site depth and shear profile also showed influence. The study did however not include the influence of varying the turbine's geometrical parameters or its operating state.

McCann [10] also presented a sensitivity study on the fatigue loading on a TST caused by surface wave-action and inflow turbulence, using a commercial BEMT design code. The study showed that there was a strong correlation between a turbine's blade root fatigue and the turbulence intensity of the flow, although the wave effects could be seen as the dominant factor in the case investigated. The study highlighted the need for a complete exhaustive study on the inflow parameters to determine the relationships of the inflow conditions to the fatigue loading, it was also recommended that other components, such as transmissions and support structures, should be investigated.

It is noted that the majority of the experimental and numerical studies presented in literature do not take into account the aforementioned non-uniformity of the loads across the rotor plane at any given instance in time. Therefore, these studies tend to neglect the additional out-of-plane bending moments on the rotor, caused by the non-uniform thrust loads, that will be transmitted to the turbine's shaft and internal components.

Based on the identified lack of knowledge on the parameter influence on hydrodynamic loads on TSTs in a global sense, the main aim of this paper is to present a method to rank the importance of the inflow, operational and geometrical parameters of a TST operating in the marine environment and to inform on the relationships between the parameter's and the output loads. Special attention is given to the parameters' influence on the variance of the loads on a turbine's components, as this was considered to be a major driver for the durability and fatigue life of a device. Furthermore, since the studies on TST loading found in literature unanimously show that the rotor thrust is the dominant load on the structure, the focus of this paper will be on the parameters' influence on the thrust load only. Finally, since the non-uniformity of the thrust loads across the rotor plane was found to be an often over-looked aspect of TST loading, the influence of the identified dominant parameter's effect on the eccentric shaft bending moments was studied in greater detail.

The results of the turbine thrust loads presented in this paper were derived using a numerical BEMT model, adapted for use on TSTs in dynamic inflow conditions. This numerical model was implemented in MATLAB, as originally described in Nevalainen et al. [14], and was based on the general architecture as presented by Masters et al. [9]. The influence the input parameters had on the loads was determined using the Morris method sensitivity analysis [15], where the fast convergence time of the numerical BEMT code was utilised to run the hundreds of model permutations needed for a statistically robust analysis of the load sensitivity. With the most influential input parameters in regards to the turbine loads identified, a detailed analysis of the influence of these 'primary parameters' on the rotor out-of-plane bending moments was performed. This gave insight into the parameters' relationship with the loads, and load variations, on the rotor which is equivalent to the loads on the turbine shaft connection.

Presented below are brief overviews of the numerical modelling techniques used, and the set-up of the sensitivity analysis by the definition of the input parameters and the output metrics studied.

2. Methods

This section presents a brief outline of the principles of the unsteady BEMT method used to derive the turbine loads including the modifications made in order to adapt it for TST applications. The general principles of the Morris method sensitivity analysis are also shown here to give the reader a basic understanding of the algorithm. The sensitivity analysis was divided