Renewable Energy 59 (2013) 105–114

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

Experimental measurements of the hydrodynamic performance and structural loading of the Transverse Horizontal Axis Water Turbine: Part 1

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ARTICLE INFO

Article history:
Received 8 July 2012
Accepted 12 March 2013
Available online 16 April 2013

Keywords:
Tidal stream energy
Cross-flow turbine
Darrieus turbine
High solidity
High blockage

ABSTRACT

This paper is the first of three, which outline the procedures and results for a set of experiments carried out on various configurations of the Transverse Horizontal Axis Water Turbine (THAWT), which is a horizontally orientated variant of the Darrieus cross-flow turbine. Tests were conducted in the combined wind, wave and current tank at Newcastle University on a 0.5 m diameter rotor, while the flow depth and velocity were varied over a range of realistic Froude numbers for tidal streams. Various configurations of the device were tested to assess the merits of varied blade pitch, rotor solidity, blockage ratio and truss oriented blades. Experiments were carried out using a speed controlled motor/generator, allowing quasi-steady results to be taken over a range of tip speed ratios. Measurements of power, thrust, blade loading and free surface deformation provide extensive data for future validation of numerical codes and demonstrate the ability of the device to exceed the Lanchester-Betz limit for kinetic efficiency by using high blockage. This paper covers the experimental procedures and results for the hydrodynamic performance for the parallel bladed variant of the THAWT device. The second paper covers the hydrodynamic loading of the parallel bladed rotor and the third covers both hydrodynamic performance and loading of the truss configured THAWT device.

1. Introduction

Tidal stream energy extraction has been identified as an economically viable contributor to the renewable power portfolio in the UK. The horizontal axis, axial flow turbine is the most common design of a tidal stream turbine. A number of variants of this type of device, which incorporate features such as flow-guiding shrouds or specific mounting techniques, have been proposed by different developers [1], but the underlying hydrodynamics remain similar for these devices. However, a drawback with such designs is that their size cannot be increased significantly, because the limited depth of flow at most sites restricts their diameter [2]. To achieve a significant scale of power generation using axial flow devices, many relatively small units would have to be deployed. An alternative approach to achieve hundreds of megawatts capacity would be to use a device which could be stretched laterally across a tidal flow. The Transverse Horizontal Axis Water Turbine (THAWT) has been proposed as a design that can be scaled in this way [3]. This device is a variant of the Darrieus concept, and incorporates a (patent pending) truss design [4] to increase the stiffness and strength of the structure (see Fig. 1). The improved structural performance allows longer units to be constructed, and reduces the overall costs of foundations, bearings, seals and generators. A full scale device might have a diameter of 10–20 m with the axis of rotation located approximately at midheight in a flow of depth of 20–50 m. Each rotor might be in the range 60–120 m long, and would consist of perhaps 4–6 “bays” of blades.

This paper is the first of three, which outline the procedures and results for a set of experiments carried out on various configurations of the Transverse Horizontal Axis Water Turbine (THAWT). This paper covers the hydrodynamic performance for the parallel bladed variant of the THAWT device, as shown in Fig. 2. The second paper covers the hydrodynamic loading of the parallel bladed rotor [5] and the third covers both performance and loading of the truss configured THAWT device [6].

Previous experimental studies of the performance of cross-flow wind devices [7,8] focus on rotors of relatively low solidities, which experience reasonably uniform flow fields. While some experimental studies of cross-flow water turbines have been conducted with higher solidities [9,10], the relationship

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http://dx.doi.org/10.1016/j.renene.2013.03.016

Nomenclature

A	cross sectional area of turbine, m^2
b	test section width, m
$B = A/hb$	turbine blockage ratio
c	blade chord length, m
$C_D = D/\left(\frac{1}{2}\rho v^2 Lc\right)$	blade drag coefficient
$C_H = P/\dot{m}g(H_1 - H_2)$	head power coefficient
$C_P = P/\left(\frac{1}{2}\rho A u_r^3\right)$	power coefficient
$C_T = T/\left(\frac{1}{2}\rho A u_r^2\right)$	thrust coefficient
d	diameter of turbine, m
D	hydrodynamic drag, N
$\mathrm{Fr} = u_r/\sqrt{gh_r}$	dimensionless Froude number
h	depth of flow, m
$H = \left(h + \frac{u^2}{2g}\right)$	total head, m
L	blade length, m
n	number of turbine blades
$\dot{m}$	channel mass flow rate, kg/s
P	measured power produced by turbine, W
P_p	flume recirculating pump power, % of maximum
T	measured thrust produced by turbine, N
r	turbine blade radius, m
$\mathrm{Re} = vc\rho/\mu$	dimensionless blade Reynolds number
$s = nc/\pi d$	turbine solidity
x	chordwise coordinate of blade profile, m
y	coordinate of blade profile normal to chord, m
u	volume averaged flow velocity, m/s
v	blade resultant flow velocity, m/s
λ	tip speed ratio
μ	dynamic viscosity of water, mPa s
ρ	density of water, kg/m^3
φ	foil fixed offset pitch angle, °

Subscripts

∞	far field, upstream flow
r	at streamwise rotor plane

between the hydrodynamic performance and structural loading has not been explored. Numerical predictions of the performance of cross-flow tidal devices have also been reported [11,12], but these have lacked experimental validation with tests of comparable blockage, solidity and Reynolds number flows.

The experimental apparatus and instrumentation are extended and improved from earlier tests reported in Ref. [3]. The results from the parallel bladed rotor are used as a basis for comparison with the truss device [6], as well as allowing the effect of configuration variations of the cross-flow device to be easily explored. These results indicate how the performance and structural loading of the parallel bladed device differ with variations in fixed offset blade pitch, rotor solidity, channel blockage and flow direction.

2. Experimental setup

2.1. Basic flume setup

The experiments on the cross-flow rotor were carried out in the combined wind, wave and current tank at Newcastle University, with plan dimensions and the turbine located as shown in Fig. 3. The power take-off and blade strain gauging instrumentation were located within streamlined fairings on either side of the rotor, which restrict the width of the channel to 1.61 metres at the turbine. These fairings extended the entire depth of the flume and were centered on the axis of the rotor. The shape of the fairing spline is defined using a cubic Bezier curve of the form

$$y(t) = (1-t)^3\mathbf{P}_0 + 3(1-t)^2 t\mathbf{P}_1 + 3(1-t)t^2\mathbf{P}_2 + t^3\mathbf{P}_3,\ t\in[0,1] \quad (1)$$

with local control points $\mathbf{P}_0$–$\mathbf{P}_3$ as shown in Table 1.

The position of the two capacitance depth probes, which measured the upstream and downstream flow depth during the course of the experiments, is also shown in Fig. 3.

2.2. Flow characterisation

The volume flow rate in the flume was measured by removing the turbine and streamlined fairings, before measuring the velocity profile at the streamwise position of the rotor. The

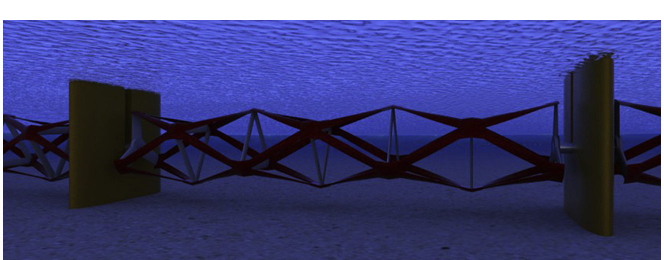

Fig. 1. Rendered image of a string of THAWT devices, provided by Kepler energy Ltd. and Mojo Maritime.

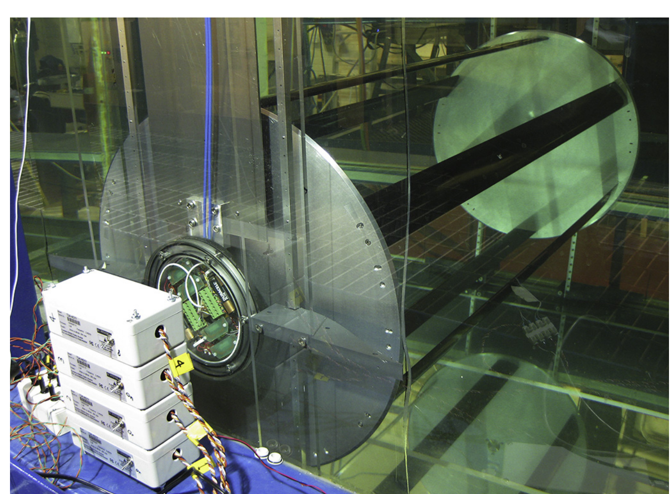

Fig. 2. Photograph of in-situ parallel bladed rotor and strain gauge instrumentation.