Renewable Energy 59 (2013) 82–91

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 3

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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 third of three, which describe the procedures and results for a set of experiments 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 instrumentation, hydrodynamic performance and loading of the truss bladed variant of the THAWT device. The first paper covers the experimental setup and hydrodynamic performance of the parallel bladed rotor and the second paper covers the instrumentation and hydrodynamic loading of the parallel bladed rotor.

1. Introduction

The abundance of tidal energy dissipation on the European continental shelf [1] has driven interest in methods of both tidal barrage and tidal stream energy extraction around the UK. The financial and environmental complications that accompany tidal barrage technology [2] have led to increased investment in tidal stream generation schemes. With the size of conventional axial flow devices limited by the depth at most tidal sites [3], many relatively small units (<5 MW) are necessary to achieve an economic scale of power generation.

The Transverse Horizontal Axis Water Turbine (THAWT) has been proposed as an alternative design to the axial flow tidal stream device [4], and can be scaled by stretching the device in the spanwise direction across a channel, using long stiff multi-bay rotors with a truss configuration of blades, as shown in Fig. 1. Unlike several other proposed designs of cross-flow tidal stream devices [5], the truss configured THAWT device uses the blades as structural members, which allows a proportion of the hydrodynamic load to be transferred to the rotor supports via axial forces, as well as bending moments.

Previous studies have shown that by using the truss configuration of blades the efficiency of the device is reduced, when compared to a parallel bladed device [4]. However, the increased power take-off due to high blockage, and the savings in cost by reducing the number of foundations, bearings, seals and generators for a given area of energy extraction are anticipated to result in a device that is economically competitive or superior to alternative designs.

This paper is the third of three, which together describe the procedures and results for a set of experiments carried out on various configurations of the THAWT device. This paper covers the experimental setup, instrumentation and analysis of the hydrodynamic performance and structural loading of the truss bladed THAWT device, shown in Fig. 2. The first paper covers the experimental setup and hydrodynamic performance of the parallel bladed rotor [6] and the second paper covers the loading and structural performance of the parallel bladed rotor [7].

2. Experimental setup

2.1. Basic flume setup and instrumentation of hydrodynamic performance

The experiments were carried out in the combined wind, wave and current tank at Newcastle University, with plan dimensions

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http://dx.doi.org/10.1016/j.renene.2013.03.012

Nomenclature

A	average cross-sectional area of turbine, m^2
b	test section width, m
$B = A/hb$	turbine blockage ratio
c	blade chord length, m
$C_A = F_A/(1/2)\rho A u_r^2$	axial blade force coefficient
$C_H = P/\dot{m}g(H_1 - H_2)$	head power coefficient
$C_N = w/(1/2)\rho c u_r^2$	blade normal force coefficient
$C_P = P/(1/2)\rho A u_r^3$	power coefficient
$C_T = T/(1/2)\rho A u_r^2$	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
$H = h + (u^2/2g)$	total head, m
L	lift force, N
n	number of turbine blades
$\dot{m} = \rho b h u_r$	channel mass flow rate, kg/s
F	resultant blade force, N
F_A	axial blade force, N
P	measured power produced by turbine, W
T	measured streamwise rotor thrust, 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 perpendicular to blade axis, m/s
w	distributed loading normal to blade chord, N/m
μ	dynamic viscosity of water, mPa s
$\lambda = r\omega/u_r$	tip speed ratio
ρ	density of water, kg/m^3
θ	blade rotation angle, °
φ	foil fixed offset pitch angle, °

Subscripts

∞	far field, upstream flow
r	at streamwise rotor plane

and the turbine located as shown in Fig. 3. Measurements were taken during the experiments of volume averaged flow velocity, upstream and downstream flow depths, rotor torque, rotor angular velocity, rotor angular position and hydrofoil loading normal to the blade chord. Details of the rotor support geometry, drive train components, depth measurement instrumentation and flow characterisation are given in Ref. [6].

2.2. Truss rotor

As shown in Fig. 2 the truss rotor consists of three bays of glass fibre composite blades, oriented as a stiff truss using triangular aluminium interbay structures. As shown in Fig. 4, at each joint the blades are offset both radially and tangentially. The end radii of the hydrofoils has been chosen so that the average blade radius is $r = 0.25$ m, to match the radius of the parallel bladed variant in Refs. [6,7]. With an individual bay length of 0.5 m the average azimuthal sweep angle of the blades is 20.4°, as shown in Fig. 5. The average rotor solidity of $s = 0.25$ is kept the same as the parallel bladed variant by matching the blade chord of 65.45 mm in the azimuthal direction, but the chord perpendicular to the blade axis is reduced to $c = 61.3$ mm, due to the blade sweep. The NACA0018 hydrofoil profile is applied on a plane normal to the blade axis, resulting in a reduced blade thickness when compared to the parallel bladed variant.

Aluminium inserts in the blade ends allow each hydrofoil to be bolted to a spherical bearing at the quarter chord point, which is then mounted in the interbay frames. The bearings are used to provide a pinned connection between the blades and the support structure. However, rotations about the blade axis are restrained with a 1 mm dowel pin towards the trailing edge of the blade. The aluminium plates into which the bearings are fixed are 10 mm wide and are joined by NACA0012 profile aluminium extrusions with a chord of 70.0 mm, to form the triangular interbays. The structures at the end of the frame also use radial arms of the extruded aluminium to connect the frame to the rotor shafts.

The rotor axis is mounted 0.425 m above the flume base, leaving a clearance of 0.175 m below and 0.325 m above to the free surface in a 1.0 m deep flow.

The NACA0018 profile used for the hydrofoils has been conformally mapped onto the average pitch circle ($r = 0.25$) of the blades using the following transformations:

$$x' = (r + y)\sin\left(\frac{x}{r}\right) \quad (1)$$

$$x' = (r + y)\sin\left(\frac{x}{r}\right) \quad (2)$$

A fixed offset pitch of $\varphi = -2°$ is applied to the blades of the truss rotor, so that at each spanwise location the hydrofoil profile is

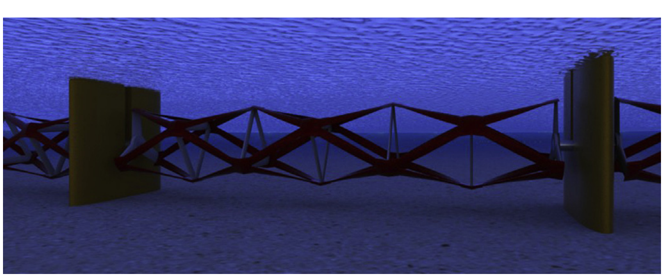

Fig. 1. Rendered image of a string of THAWT devices, provided by Kepler Energy Ltd. and Mojo Maritime.

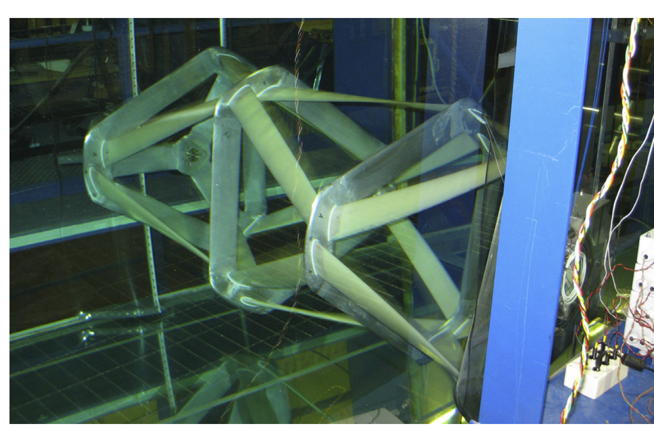

Fig. 2. Photograph of in-situ truss bladed rotor and strain gauge instrumentation.