ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Analysis of cavitation for the optimized design of hydrokinetic turbines using BEM

Paulo Augusto Strobel Freitas Silva [a], Léo Daiki Shinomiya [b], Taygoara Felamingo de Oliveira [a], Jerson Rogério Pinheiro Vaz [b], André Luiz Amarante Mesquita [c,*], Antonio Cesar Pinho Brasil Junior [a]

[a] University of Brasília – Faculty of Mechanical Engineering, Campus Darcy Ribeiro, Brasília, DF 70910-900, Brazil
[b] Federal University of Pará – Faculty of Mechanical Engineering, Av. Augusto Correa, N 1 – Belém, PA 66075-900, Brazil
[c] Federal University of Pará – Amazon Development Center in Engineering – NDAE – Vila Permanente 68.464-000 Tucuruí, PA, Brazil

HIGHLIGHTS

- Optimization of horizontal-axis hydrokinetic turbines considering cavitation.
- The method corrects the blade chord by a modification on the local thrust coefficient in order to prevent cavitation.
- The minimum pressure coefficient is the criterion used for the identification of cavitation on hydrokinetic blades.
- The method is evaluated by CFD using the Rayleigh-Plesset model to predict the vapor production rate.
- The approach is helpful to design energy generation technologies applied to river, tidal and marine currents.

ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form 16 February 2016
Accepted 17 February 2016
Available online xxxx

Keywords:
Hydrokinetic turbines
Cavitation
Blade optimization
BEM
Rayleigh-Plesset model

ABSTRACT

Hydrokinetic turbines are a promising technology for renewable energy production from river, tidal and marine currents. This paper proposes an innovative approach applied to optimization of horizontal axis hydrokinetic turbines (HAHTs) considering the possibility of cavitation. The minimum pressure coefficient is the criterion used for identifying cavitation on blades. Blade Element Momentum (BEM) theory is employed for the rotor design. During the optimization procedure, chord length at each blade section is corrected by a modification on the local thrust coefficient in order to prevent cavitation. The hydraulic parameters as lift, drag and minimum pressure coefficients are calculated by XFoil. Additionally, Computational Fluid Dynamics (CFD) techniques are used to validate the proposed methodology. Cavitation volume in the water flow through the rotor, with and without geometrical modifications, is evaluated using a Reynolds Averaged Navier–Stokes (RANS) approach coupled to the Rayleigh-Plesset model to estimate the vapor production rate. The methodology is applied to the design of a 10 m diameter Hydrokinetic Turbine (HT) rated to 250 kW output power, for a flow velocity of 2.5 m/s. The flow around the optimized rotor presents a reduction of the vapor volume without a major variation upon the turbine output power. A comparison with the Horizontal Axis Rotor Performance Optimization (HARP_opt) code was carried out, demonstrating good behavior. CFD simulations revealed that the proposed design method minimizes cavitation inception, yielding a useful tool for efficient HT design at rated conditions.

1. Introduction

Hydrokinetic turbines (HTs) have recently been used as converters of river, tidal and marine currents to electrical energy [1,2]. This technology has become significant due to the increasing use of renewable energy sources with low environmental impact. The power coefficient maximization is fundamental in HT design in order to improve energy extraction from water flow. However, for design, it is important to take into account the possibility of cavitation. As in the design of classical hydraulic turbines [3], cavitation inception is assumed to occur on a blade section when the minimum local pressure falls below the vapor pressure of the fluid. Cavitation inception can be predicted by comparing the local minimum pressure coefficient with the cavitation number. The chances of cavitation occurring increases more toward the blade

* Corresponding author.
E-mail address: andream@ufpa.br (A.L. Amarante Mesquita).

http://dx.doi.org/10.1016/j.apenergy.2016.02.098
0306-2619/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

Abbreviations

BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
DWST	Distance from water surface to tip blade
HAHT	Horizontal Axis Hydrokinetic Turbine
HT	Hydrokinetic Turbine
HARP_opt	Horizontal Axis Rotor Performance Optimization
LES	Large Eddy Simulation
RANS	Reynolds Averaged Navier–Stokes
SST	Shear Stress Model

Arabic symbols

a, a'	axial and tangential induction factor
a_{opt}	optimum axial induction factor
B	number of blades
c	chord (m)
c^{uc}, c^{co}	uncorrected and corrected chord (m)
c_{opt}	optimal chord (m)
C_L, C_D	lift and drag coefficients
C_P	pressure coefficient
C_{power}	power coefficient
C_{Pmin}	minimum pressure coefficient
C_n	normal force coefficients
C_T	thrust coefficient
D	turbine diameter (m)
f_s	safety factor
f	force per unit of volume (N/m^3)
F	Prandtl's tip loss factor
F_c	empirical constant of the cavitation model
g	gravity acceleration (m^2/s)
h, H	distance between free surface and turbine radial position (m)
$\dot{m}_l, \dot{m}_v$	rate of change mass per unit of volume for liquid and vapor phases
Ns	section number
N_B	number of bubbles per unit of mixture volume
p_{atm},	atmospheric pressure (Pa)
p_0, p_∞	reference pressure upstream(Pa)
p_v	vapor pressure (Pa)
r, R	radial position and turbine radius (m)
r_l, r_v	volume fraction of liquid and vapor
r_{nuc}	volume fraction of nucleation sites
R_B	bubble radius (m)
Re	Reynolds number
Re_c	local Reynolds number based on the airfoil chord
u_i	velocity component (m/s)
u'_i	velocity fluctuations (m/s)
u^+	friction velocity (m/s)
$\overline{u'_i u'_j}$	Reynolds stress tensor (m^2/s^2)
V_0	velocity in ambient free stream (m/s)
V_{CAV}	cavitation velocity
V_B	bubble volume (m^3)
W	relative velocity (m/s)
Δy	distance of nearest wall (m)
y^+	dimensionless wall distance

Greek symbols

β	twist angle (deg)
β_{opt}	twist angle (deg)
λ	tip-speed ratio
μ	dynamic viscosity (St)
ν	kinematic viscosity (St)
ρ	density (kg/m^3)
ρ_m	mixture density (kg/m^3)
σ	cavitation number
σ_s	surface tension coefficient
τ_{ij}	Reynolds stress tensor (m^2/s^2)
Ω	angular velocity of the rotor (rad/s)

tip due to low immersion depth, which is an important issue to be assessed on HT design. Molland et al. [4] showed that the cavitation-free region changes with respect to the hydrofoil camber. This observation was confirmed by Batten et al. [5] who show that the cavitation characteristics for a particular section can be described by a minimum pressure envelope or cavitation-free region, as a function of the section cavitation number. Since the section lift coefficient is a function of the pressure distribution, this region can be represented as a limiting lift coefficient envelope for a given cavitation number. In a complementary work, Bahaj et al. [6] carried out an experimental study of cavitation inception on HT blades and concluded that the cavitation does not appear until the cavitation number has been reduced to about 0.9. When the cavitation number is reduced to below 0.4, there is cavitation on the suction side over 10–15% of the outer part of the blade. These authors suggest that cavitation typically appears at tip-sped ratio ($\lambda = \Omega R/V_0$) values greater than about 7.0, which indicates a very high thrust loading, as discussed by Goundar et al. [7].

In general, the optimization models of HT blades are based on BEM theory. These methods are frequently used for design and analysis of hydrokinetic rotors. BEM is an integral method, with semi-empirical information from hydrodynamic forces on hydrofoil sections, combined with two-dimensional airfoil flow models or experimental data for section lift and drag [8,9]. Such models are direct applications of the approaches developed for wind turbines, and are employed for design including optimization models for chord and twist angle distributions, taking into account the influence of swirl velocity in the wake [10]. BEM is also applied successfully in the design of hydrokinetic turbines [5,7,11]. Sale et al. [12] show a method of optimizing hydrokinetic blades based on genetic algorithms coupled to the BEM, in which the cavitation effect was employed. CFD is also used for the analysis of 3-D flow through HTs as described in Refs. [13,14]. CFD is generally used to analyze turbine performance and flow field, e.g., Kang et al. [15] developed a detailed study using large-eddy simulation (LES) in order to investigate the structure of turbulence in the wake meandering of an axial turbine. Lee et al. [16] used the CFD approach to obtain a new blade design to delay cavitation inception. The modified design is a raked tip turbine, which does not degrade the turbine performance.

This paper proposes a new methodology with low computational cost and easy implementation, using BEM to optimize hydrokinetic rotors considering the minimum pressure coefficient as criterion to avoid cavitation. A correction on the local thrust coefficient is performed, in order to calculate the optimum shape of the hydrokinetic blade. In the computational algorithm, lift and drag coefficients are calculated by XFoil [17], which is a linear vorticity-stream function panel method with an integral boundary layer and wake model. Both corrected and uncorrected rotor designs are then analyzed by CFD through the Reynolds Averaged Navier Stokes (RANS) equations using the Rayleigh-Plesset model to estimate the vapor production rate. This step is computed by commercial code ANSYS CFX.

Please cite this article in press as: Silva PASF et al. Analysis of cavitation for the optimized design of hydrokinetic turbines using BEM. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.02.098