Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 277 – 282

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Design of Hydrokinetic Turbine Blades Considering Cavitation

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

[a] *Universidade Federal do Pará, Rua Augusto Corrêa, 01 - Guamá. CEP 66075-110. Belém - Pará - Brasil*
[b] *Universidade de Brasília,* Campus *Universitário Darcy Ribeiro,CEP 70910-900. Brasília -DF - Brasil*

Abstract

The cavitation is a phenomenon that must be considered into a hydrokinetic turbines design. This assumption has been explored in the last years, principally for the turbine with large diameter, once the relative velocity near the hydrokinetic blade tip is increased, resulting in large angle of attack. Therefore, a mathematical approach for design of hydrokinetic blades is presented. In which a methodology for cavitation prevention is employed. The approach uses the minimum pressure coefficient criterion as a cavitation limit for the flow on the blades. The proposed methodology modifies the local relative velocity in order to prevent the cavitation occurrence on each blade section. The results are compared with data from hydrokinetic turbines designed using the classical Glauert's optimization, on which the proposed approach provides good performance, where the chord distribution along the blade is corrected, and can be used for efficient hydrokinetic turbines design.

Keywords: Hydrokinetics Turbines, Cavitation, Blades Optimization, Marine Energy.

1. Introduction

Hydrokinetic turbines have been recently used as converters of marine energy in electricity [1]. These technologies have become significant due to the increasing use of renewable energy sources with low environmental impact. The maximization of the power coefficient is fundamental in the hydrokinetic turbine design in order to improve the extraction of energy from water flow in rivers, marine and tidal currents [2, 3]. The present work describes an approach applied to the hydrodynamic optimization of horizontal-axis hydrokinetic turbines rotors, considering the search of optimum shape design of the blade with a correction to avoid the blade cavitation. In general the optimization models of hydrokinetic turbine blade are based on the BEM (Blade Element Momentum) method. These models are the most frequently

* Corresponding author. Tel.: +55-91-3201-7962; fax: +55-91-3201-7109.
*E-mail address:*andream@ufpa.br.

doi:10.1016/j.egypro.2015.07.343

used by scientific and marine power industry communities for design and analysis of hydrokinetic rotors. BEM method is essentially an integral method, with semi-empirical information from hydrodynamics forces in hydrofoil sections, issued from two-dimensional airfoil flow models or experimental data [4, 5]. Such models are direct applications of the approaches developed for the case of wind turbines, e.g. Rio Vaz et al. [6] present an optimization model for the chord and twist angle distribution of horizontal axis wind turbine blades, taking into account the influence of the wake of the rotor. For the hydrokinetic turbines design, it is important to take into account the possibility of cavitation [7], since, in water, the emergence of the pressure field near to the vapor pressure frequently occurs, causing undesirable erosion on the rotor blades and loss of the produced power [8]. In the literature there are few publications that consider the cavitation occurrence in hydrokinetic turbines design. Goundar et al. [9] show numerical and experimental studies on hydrofoils for marine current turbines, where a hydrofoil is designed to perform well at tip-speed ratios between 3 and 4, avoiding cavitation inception and also having good hydrodynamic performance. Batten et al. [10] developed a study for the prediction of cavitation for certain cases with relatively shallow tip immersion. It was found that cavitation could be avoided with the use of suitable designs and choice of 2D sections. Sale et al. [11] show a method of optimizing hydrokinetic blade using genetic algorithms to design cavitation free rotors and BEM method to determine the produced power. Thus, this work proposes a methodology for design of hydrokinetic rotors so that to consider a criteria of minimum pressure coefficient as a limit for a flow without cavitation on the hydraulic profile. The proposed model is an extension of the classical Glauert's optimization model [12], on which the effect of cavitation is considered. A correction on the thrust coefficient (or load factor) is performed, where the minimum pressure coefficient is used as a limit in order to avoid the blade cavitation. In the calculation of the optimum shape of the hydrokinetic blade, the chord and twist angle are corrected. The results are discussed and compared with the Glauert's optimization model showing good performance.

2. Mathematical Model

2.1. BEM Method

The Blade Element Momentum (BEM) is a widely used approach for the analysis and design of hydrokinetic turbines. This approach, combining the basic principles from both blade element and momentum theories, is inherently steady, two dimensional, stems from the equivalence between the circulation and momentum theories of lift, and allows estimating the inflow distribution along the blade. Thus, it is possible to determine the optimal geometry of a hydrokinetic blade using BEM method. As it is well known, in this method the blade is divided into a number of elementary stream tubes (called "strips") along the radius, where a force balance is applied involving two-dimensional profile lift and drag along with the thrust and torque produced within the strip. At the same time, a balance of axial and angular momentum is applied. According Rio Vaz et al. [6], the BEM present good agreement with experimental data. Therefore, the coefficients of normal and tangential forces are defined by:

$$C_n = \frac{F_n}{\frac{1}{2}\rho W^2 c} = C_L \cos\phi + C_D \sin\phi\,, \tag{1}$$

$$C_t = \frac{F_t}{\frac{1}{2}\rho W^2 c} = C_L \sin\phi - C_D \cos\phi\,, \tag{2}$$

where F_n and F_t is the normal and tangential forces, ρ is the density, c is the chord, C_L and C_D is the lift and drag coefficients, respectively. The relative velocity, W, is given by:

$$W=\sqrt{[V_0(1-a)]^2+[\Omega r(1+a')]^2}\ , \tag{3}$$

where V_0 is the free stream velocity, Ω is the angular speed, r is the radial position, a and a' is the axial and tangential factors, respectively. The angle of flow ϕ is defined as:

$$\tan\phi=\frac{(1-a)V_0}{(1+a')\Omega r}\ . \tag{4}$$

Thus, it is possible to express the thrust and torque coefficients, C_T and C_M, as

$$C_T=\frac{dT}{\frac{1}{2}\rho V_0^2 dA}=\left(\frac{W}{V_0}\right)^2\sigma C_n=\left(\frac{V_1}{V_0\sin\phi}\right)^2\sigma C_n\ , \tag{5}$$

$$C_M=\frac{dM}{\frac{1}{2}\rho V_0^2 dA}=\left(\frac{W}{V_0}\right)^2 r\sigma C_t=\left(\frac{V_1}{V_0\sin\phi}\right)^2 r\sigma C_t\ , \tag{6}$$

where $\sigma=Bc/2\pi r$, C_T is the thrust coefficient, C_M is the torque coefficient, dT and dM are the differential of thrust and torque, respectively, acting over a blade section. The axial and tangential induction factors (a and a') are obtained classically by follow relations:

$$\frac{a}{1-a}=\frac{\sigma C_n}{4F\sin^2\phi}\ , \tag{7}$$

$$\frac{a'}{1+a'}=\frac{\sigma C_t}{4F\sin\phi\cos\phi}\ . \tag{8}$$

where F is the Prandlt tip-loss factor. The Prandlt tip-loss model is the most accepted correction employed and is usually taken as corresponding to a model of the flow for a finite number of blades [6].

The power coefficient (Cp) of the turbine can be expressed as a function of the induction factors, since the aerodynamic characteristics of the blade profile are available. Thus, the Cp is given by:

$$\mathrm{Cp}=\frac{P}{\frac{1}{2}\rho A V_0^3}=\frac{8}{\lambda^2}\int_0^{\lambda} a'(1-a)x^3 dx\ , \tag{9}$$

where $x=\Omega r/V_0$ and $\lambda=\Omega R/V_0$.

2.2. Cavitation Prevention Criterion

Cavitation is a phenomenon that should be considered on the hydrokinetic turbines design [9]. Its effect causes structural damage to turbine blades, reduces its performance, and in general, is originated in the blade section where the pressure decreases below the vapor pressure of the fluid. The liquid vaporizes instantly, forming a cavity of vapor, which alters the flow. The shape and size of the bubble also varies as consequence of the action of the pressure and velocity fields. When the vapor cavity implodes, the pressure on the blade surface increases, promoting erosion on the blade. The failures caused, decrease the lift and increase the drag, leading to a reduction of the turbine efficiency. It can be predicted by comparing the local pressure distribution with the cavitation number [11]. The cavitation number σ, is classically defined as

$$\sigma = \frac{p_{atm} + \rho g h - p_v}{\frac{1}{2}\rho W^2}, \tag{10}$$

where p_{atm} is the atmospheric pressure, $\rho$is the water density, g is the local gravity, $h$is the distance between the free surface and the radial position on the hydrokinetic rotor, p_v is the vapor pressure at flow temperature, and W is the relative velocity on a blade section. There will be cavitation on a blade section if the local minimum pressure coefficient, Cp_{min}, is lower than the cavitation number σ. The minimum pressure coefficient is an important parameter at the hydrokinetic turbines design. It gives information on the hydrodynamic loading of the blades, and it is defined as the minimum value of the pressure coefficient on the suction side of the blade section. This coefficient can be used as a criterion to avoid the cavitation, given by $\sigma + C_{Pmin} \geq 0$ [13]. Using the definition of pressure coefficient and the expression for the cavitation number, it is possible to define a critical velocity which produces a local pressure equal to vapor pressure as

$$V_{CAV} = \sqrt{\frac{P_{atm} + \rho g h - P_v}{\frac{1}{2}\rho C_{Pmin}}}. \tag{11}$$

Thus, the criterion to avoid cavitation requires that relative velocity, W, at each blade section along the radial coordinate, must be smaller than the velocity V_{CAV}. In other words, if $W \geq V_{CAV}$ then the local relative velocity must be corrected.In the context of BEM methods, it’s can be made by replacing W by $W_{CAV} = (1 - f_S)V_{CAV}$ in the calculus of the chord lenght, alway that $W \geq V_{CAV}$ .Here, f_S is an arbitrary safety factor defined in the interval [0,1[. Replace W by W_{CAV} in sections where $W \geq V_{CAV}$ leads to an increase in the chord length. The Eq. (5) can be used to provide an expression for c in terms of $(V_0 / W)^2$ and the other quantities in right hand side of Eq. (11). Thus, in the blade sections where the criterion is achieved, is easy to show that the ratio between the corrected and uncorrected chord lengths, c^{co} and c^{uc}, is

$$\frac{c^{co}}{c^{uc}} = \left[\frac{W}{(1 - f_S)V_{CAV}}\right]^2. \tag{12}$$

In the blade sections, which satisfies the cavitation criterion, the relative velocity W is greater than V_{CAV}, and one conclude that $c^{co} \geq c^{uc}$.

3. Results and discussions

In order to evaluate the performance of the optimization model with cavitation was considered a horizontal-axis hydrokinetic turbine using the hydrofoil NACA 65_3− 618 with Reynolds number of 3×10^6, where the design parameters are described in Table 1. The hydrodynamic parameters such as the lift, drag and minimum pressure coefficients were obtained using the free software XFOIL, which is a coupled panel/viscous code developed at MIT [17]. XFOIL is a collection of programs for airfoil design and analysis for incompressible/compressible viscous flows over an arbitrary airfoil. In this code, a zonal approach is used to solve the viscous flow indirectly and an equivalent inviscid flow is postulated outside a displacement streamline that includes the viscous layer, becoming a powerful software for aerodynamic design, and present good agreement when compared with experimental data[15].

Table1: Design parameters used in the simulation of the horizontal-axis hydrokinetic turbine.

Parameters	Values
Turbine diameter (D)	10.0 m
Hub diameter (d)	1.5 m
Number of blades	3
Water velocity (V_0)	2.5 m/s
Water density (ρ)	997 kg/m^3
H	6 m
P_{atm}	1x10^5 Pa
P_v	3.17x10^3 Pa
Gravity (g)	9.81 m/s^2
Safety factor (f_S)	5%
Constant rotational speed	35 rpm

Table 2 shows the hydrokinetic rotor geometry, Reynolds number ($Re_c = Wc/v$, where v is the kinematic viscosity), minimum pressure coefficient and cavitation number in relation to the radial position. Fig. 1a shows that the cavitation occurs approximately at 70% of the blade for the rotor operating at 35 rpm. The model promotes the correction on the blade chord as consequences of modification on the relative velocity, as shown in Fig. 1b. This occurs due to the relative velocity, become higher than the cavitation velocity. For radial positions, r/R, higher than 0.7, the term $\left\{W/\left[\left(1-f_S\right)V_{CAV}\right]\right\}^2$ is higher than 1. After correcting, the relative velocity takes values always lower than V_{CAV}.

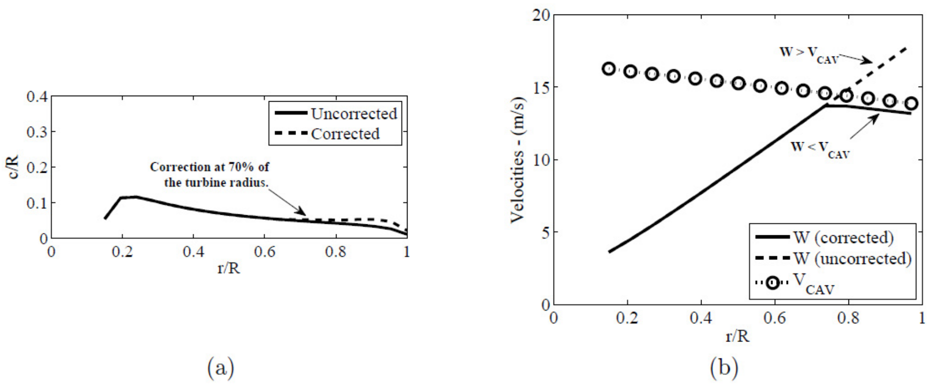


Fig. 1.(a) Chord distribution. (b) Relative and cavitation velocities as a function of the radial position.

4. Conclusion

The model described in this work is an approach to be used in the design of hydrokinetic turbines blades, which corrects the shape of the blade, aiming to prevent the cavitation. The present technique is an extension of the classical Glauert's optimization [12], on which is imposed a correction scheme in order to consider the occurrence of cavitation on the load factor (thrust coefficient). This model promotes a modification on the local chord length of the blade, without major changes on the power coefficient of the turbine. The main contribution of this work is a criterion to identify the blade sections in which cavitation may occur, where the chord length is corrected by the term $\left\{W/\left[\left(1-f_S\right)V_{CAV}\right]\right\}^2$. It is important to note that the twist angle not presents major alterations due to the correction to influence directly the chord distribution. Therefore, the present work is a tool, which can be helpful to those that have to pretension of develop technologies to the use of marine, river and tidal energies. However, some limitations should be analyzed carefully, as following: (1) develop comparisons with numerical and experimental data; (2) promoting analysis of the model at the off design condition using the BEM method.

5. Copyright

Acknowledgements

The authors would like to thanks CNPq, CAPES, PROPESP/UFPA and ELETRONORTE for financial support.

References

[1] Mycek, P., Gaurier, B., Germain, G., Pinon, G. and Rivoalen, E. Numericaland experimental study of the interaction between two marine current turbines.*International Journal of Marine Energy*2013; Vol. 1, p. 70-83.

[2] Bahaj A.S. Generating electricity from the oceans. *Renewable and Sustainable EnergyReviews* 2011; 15:3399-3416.

[3] Gney, M.S., K. Kaygusuz, K. Hydrokinetic energy conversion systems: a technologystatus review. *Renewable and Sustainable Energy Reviews* 2010; 14:2996-3004.

[4] Mesquita, A. L. A. and Alves, A. S. G. An Improved Approach for PerformancePrediction of HAWT Using Strip Theory.*Wind Engineering* 2000; Vol. 24, No. 6.

[5] Vaz, J. R. P., Pinho J. T. and Mesquita, A. L. A.An extension of BEM methodapplied to horizontal-axis wind turbine design. *Renewable Energy*2011;(36) 1734-1740.

[6] Rio Vaz, D. A. T. D, Vaz, J. R. P., Mesquita, A. L. A., Pinho, J. T., Brasil, A. C. P.Optimum Aerodynamic Design for Wind Turbine Blade with a Rankine Vortex Wake.*Renewable Energy* 2013; vol 55, pp-296-304.

[7] Gaden, D. An Investigation of River Kinetic Turbines: Performance Enhancements, Turbine Modeling Tech-niques, and an Assessment of Turbulence Models.*M.Scthesis, University of Manitoba*2007.

[8] Bahaj, A.S., Molland, A.F., Chaplin, J.R. and Batten, W.M.J. Power and thrustmeasurements of marine current turbines under various hydrodynamic flow conditionsin a cavitation tunnel and a towing tank.*Renewable Energy*2007;Vol. 32(3), p. 407-426.

[9] Goundar, J. N., Ahmed, M. R. and Lee, Y. H. Numerical and experimental studieson hydrofoils for marine current turbines. *Renewable Energy*2012;vol 42, pp-173-179.

[10] Batten, W.M.J., Bahaj, A.S., Molland, A.F., Chaplin, J.R. The prediction ofthe hydrodynamic performance of marine current turbines.*Renewable Energy*2008;vol 33,pp-1085-1096.

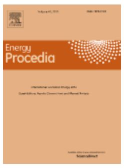
[11] Sale, D., Jonkman, J., Musial, W.Hydrodynamic Optimization Method and DesignCode for Stall-Regulated Hydrokinetic Turbine Rotors. ASME 28th *InternationalConference on Ocean, Offshore, and Arctic Engineering Honolulu*, Hawaii.31 May to 5June2009.

[12] Glauert, H. *The elements of airfoil and airscrew theory*. Cambridge: CambridgeUniversity Press1926.

[13] Cruz, A. G. B., Mesquita, A. L. A., Blanco, C. J. C.Minimum Pressure CoefficientCriterion Applied in Axial-Flow Hydraulic Turbines, *Journal of the Brazilian Society ofMechanical Sciences and Engineering*2008, Vol. 30, No. 1, pp-30-38.

[14] Hansen, M. *Aerodynamics of wind turbines*. Earthscan 2nd ed2008.

[15] Benini, E. Significance of blade element theory in performance prediction of marinepropellers. *Ocean Engineering*2004, 31, 957-974.



Biography

Obtained BSc in mechanical engineering (1984), MSc in aerospace engineering (1987), in Brazil, and PhD from Grenoble Institute of Technology, France (1992). At present is Associate Professor at Federal University of Pará, Brazil. His research areas are turbomachinery, renewable energy, multiphase flows and bulk solid flows.