AN APPROACH FOR THE OPTIMUM HYDRODYNAMIC DESIGN OF HYDROKINETIC TURBINE BLADES

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ABSTRACT

This work aims to develop a simple and efficient mathematical model applied to optimization of horizontal-axis hydrokinetic turbine blades considering the cavitation effect. The approach uses the pressure minimum coefficient as a criterion for the cavitation limit on the flow around the hydrokinetic blades. The methodology corrects the chord and twist angle at each blade section by a modification on the local thrust coefficient in order to takes into account the cavitation on the rotor shape. The optimization is based on the Blade Element Theory (BET), which is a well known method applied to design and performance analysis of wind and hydrokinetic turbines, which usually present good agreement with experimental data. The results are compared with data obtained from hydrokinetic turbines designed by the classical Glauert's optimization. The present method yields good behavior, and can be used as an alternative tool in efficient hydrokinetic turbine designs.

Keywords: hydrokinetic turbines, cavitation effect, blades optimization, renewable energy

NOMENCLATURE

Cp	pressure coefficient
C_{POT}	power coefficient
Cp_{min}	pressure minimum coefficient
CP_{opt}	optimal power coefficient
fs	security factor
R	rotor radius, m
r	local rotor radius, m
c	chord length, m
a	axial induction factor
a'	tangential induction factor
g	gravity, m/s²
W	relative velocity, m/s
V_{cav}	cavitation velocity, m/s
V_0	input velocity, m/s
p_0	pressure far field, Pa
p_{atm}	atmospheric pressure, Pa
p	blade surface local pressure, Pa
p_v	vaporization pressure, Pa
p_c	cavitation pressure, Pa
h	head water level at blade section, m
H	head water level at rotor axis, m
L	lift force, N
D	drag force, N
Fn	normal force, N
Ft	tangential force, N
Re	Reynolds number
rpm	revolutions per minute

Greek symbols

α	angle of attack, deg
β	blade pitch angle, deg
Ω	turbine rotation, rpm
ω	angular velocity, rad/s
ϕ	angle between W and the plane of rotation, deg
σ	cavitation number
ρ	density, kg/ m^3

INTRODUCTION

The hydrokinetic turbine technology has been attracted great attention due to the use of low environmental impact energy source. Such interest is reasonable, since there is an enormous stored hydrokinetic energy available in rivers, tides and oceans around the world. In Brazil, such energy availability can be typically found in North region, where the Amazon river is the largest in water volume, as well as in length and in flow rate, being highly connected in a huge net. Thus, the present optimization methodology aims to develop a mathematical approach for hydrokinetic rotors design taking into account the pressure minimum coefficient as a limit of flow without cavitation on the hydraulic profile. The proposed approach is an extension of the classical Glauert's optimization (Batten et al, 2008), on which the cavitation is considered. The methodology present low computational cost and easy implementation as well. A correction on the thrust coefficient (or load factor) is performed, where the pressure minimum coefficient is coupled in the load factor in order to avoid the cavitation phenomenon on low-pressure region along the rotor radial position. In the calculation of the optimum blade shape, the chord and twist angle are corrected through the control carried out between the relative and cavitation velocities. The results are compared with the Glauert's optimization yielding good behavior.

THEORY

The cavitation is a phenomenon that has been analyzed carefully in the hydrokinetic turbines design (Goundar et al, 2012). It can be predicted by comparing the local pressure distribution with the cavitation number (Sale et al, 2009). The cavitation number, σ, is classically defined as:

$$\sigma = \frac{p_{atm} + \rho g h - p_v}{\frac{1}{2}\rho W^2} \qquad (1)$$

where p_{atm} is the atmospheric pressure, ρ is the water density, h is the distance between the free-surface and the radial position on the hydrokinetic rotor, p_v is the vapor pressure, and W is the relative velocity on a blade section. The cavitation occur if the local pressure minimum coefficient, Cp_{min}, becomes lower than the cavitation number, σ. Figure 1 illustrates the pressure coefficient curve distribution around of a typical rotor blade section, being Cp_{min} defined as the minimum value of the pressure coefficient on the blade suction side, which can be used to avoid the cavitation (Cruz et al, 2008). Hence, the criterion is:

$$\sigma + C_{Pmin} \geq 0 \qquad (2)$$

where the pressure minimum coefficient is taken as $C_{Pmin} = \min(C_p)$, and the pressure coefficient is defined as:

$$C_P = \frac{p - p_0}{\frac{1}{2}\rho W^2} \qquad (3)$$

Thus, combining Eqs. (1) and (2) it is possible to define the cavitation velocity, which becomes:

$$V_{CAV} = \sqrt{\frac{P_{atm} + \rho g h - P_v}{\frac{1}{2}\rho C_{Pmin}}} \qquad (4)$$

To apply this criterion, in this work is proposed the following expression:

$$W = (1 - f_S)V_{CAV} \qquad (5)$$

where f_S is an arbitrary safety factor, defined in the interval [0, 1[on the blade element.

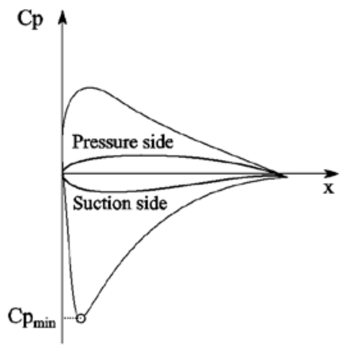
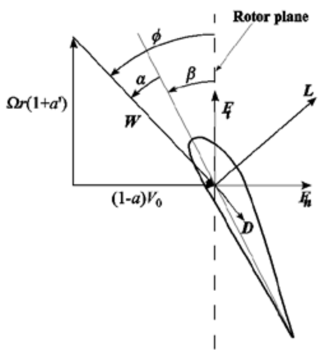


Figure 1. Illustration of the pressure minimum coefficient around rotor blade section.

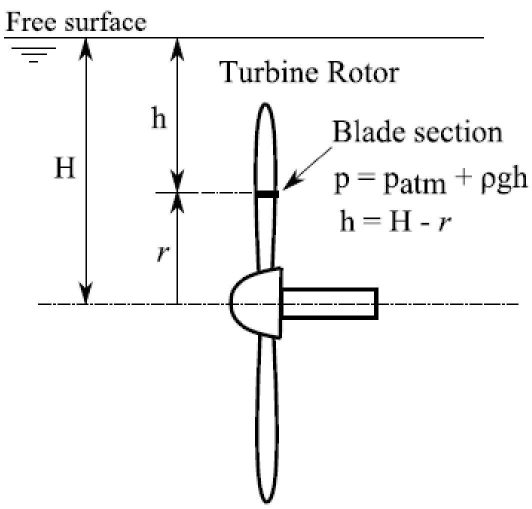
The relative velocity, *W*, is given directly by the velocity diagram shown in Fig 2a. Such parameter is computed by BET, which is a widely used approach for the analysis and design of hydrokinetic turbines. This approach, combining the basic principles from both blade element and momentum theories. It is inherently steady, one dimensional, stems from the equivalence between the circulation and momentum theories of lift, and allows estimating the inflow distribution along the blade.

$$W = \sqrt{[V_0(1-a)]^2 + [\Omega r(1+a')]^2} \qquad (6)$$

Figure 2b illustrates the static pressure condition on an elementary blade section. The hydraulic pressure varies along the rotor blade, and the cavitation is more likely at the tip end of the top blade, on which the static pressure is lower.



(a)



(b)

Figure 2. (a) Velocity diagram of the rotor blade section (b) and illustration of pressure minimum coefficient.

Equation (5) intends to avoid the cavitation by controlling the relative velocity, *W*, in each blade section, which must be smaller than the velocity cavitation, V_{CAV}.

RESULTS AND DISCUSSION

In order to evaluate the performance of the optimization model with cavitation a horizontal-axis hydrokinetic turbine was considered. The rotor uses the hydrofoil NACA 65_3–618 with Reynolds number of 3×10^6, where the design parameters are available in Tab. 1. The hydrodynamic parameters such as the lift, drag and pressure minimum coefficients was obtained using the free software XFOIL, which is a coupled panel/viscous code developed at MIT (Drela, 1989). XFOIL is a collection of programs for airfoil design and present good agreement when compared with experimental data (Benini, 2004).

Table 1. Design parameters used in the simulation of the horizontal-axis hydrokinetic turbine.

Parameters	Values
Turbine diameter (D)	6.0 m
Hub diameter	0.6 m
Nº of blades	3
Water velocity (V_0)	2.5 m/s
Water density (ρ)	997 kg/m³
H	4 m
P_{atm}	10^5 Pa
Pv	3.17×10^5 Pa
Gravity (g)	9.81 m/s²
Cavitation number (σ)	3,1718
Safety factor	5%

To evaluate the cavitation limit for a given operational condition, a characteristic curve was generated, which relates the optimum power coefficient with the rotational speed. In this case, the Cp_{opt} was computed varying only the rotational speed and keeping others design parameters constants. The result is shown in Figure 3. The rotational speed on the cavitation limit is 40 rpm, and the optimum power coefficient was approximately of 43.8%. This result depicts that when the turbine works over this rotational speed limit, it is susceptible to cavitation.

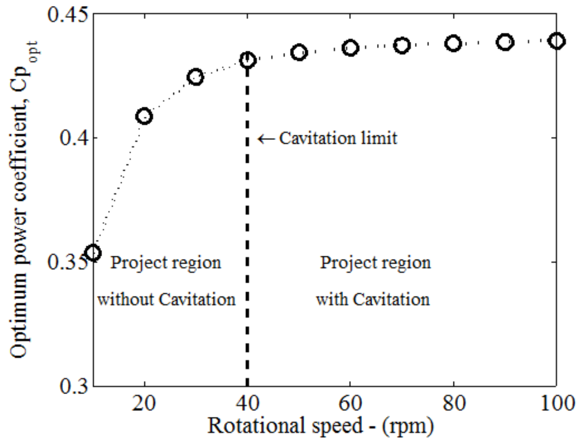
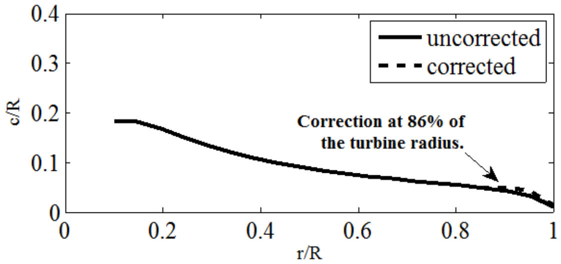
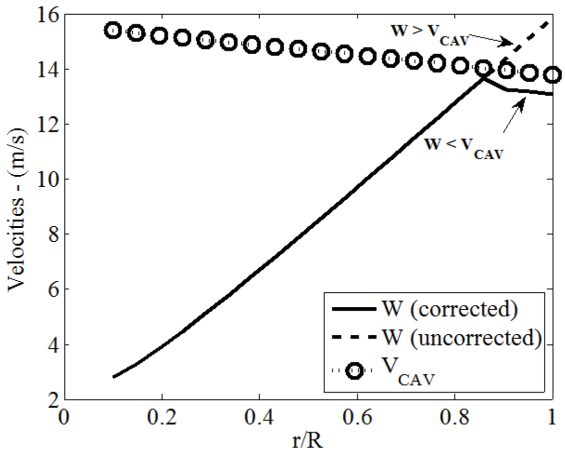


Figure 3. Optimum power coefficient as a function of the rotational speed.

To analyse the turbine design under cavitation effect, two rotational speeds (50 rpm and 75 rpm) were approached. The assessment takes into account the C_{Pmin} and the Reynolds number (Re = Wc/ν, where ν is the kinematic viscosity) related to the local chord, which is variable on the radial position. Figure 4a shows that the cavitation occurs approximately on 17^{th} section of the blade for the rotor running at 50 rpm, and on 12^{th} section of the blade at 75 rpm. The model adjust the blade chord because the relative velocity is modified in the iteractive procedure, as shown in Figure 4b. Figure 5 shows the results for the rotor operating at 75 rpm. In this case, the correction is more intense due to the increase of the rotational speed (Figure 5a). This occurs because the relative velocity becomes higher than the cavitation velocity, as shown in Fig. 5b.

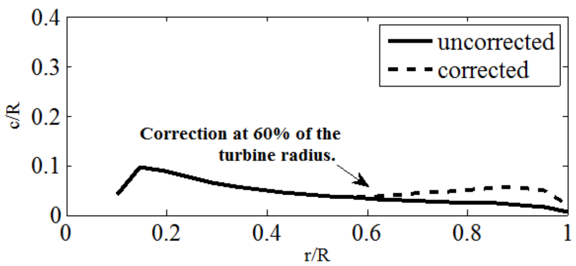


(a)

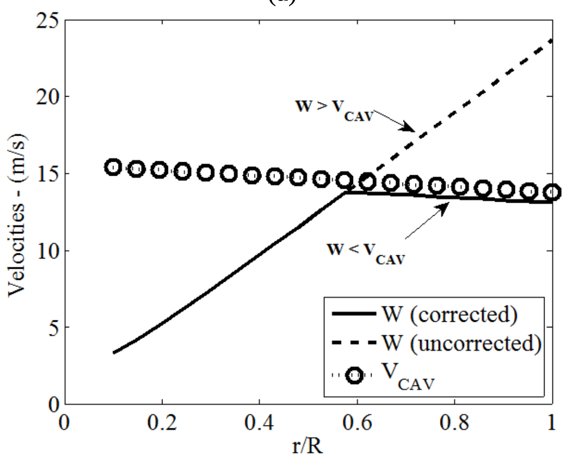


(b)

Figure 4. (a) Chord correction at 17th section of the blade. (b) Relative and cavitation velocities as a function of the radial position for the rotational speed of 50 rpm.



(a)



(b)

Figure 5. (a) Chord distribution at 12th section of the blade. (b) Relative and cavitation velocities as a function of the radial position for the rotational speed of 75 rpm.

CONCLUSIONS

The optimization model described in this work is an alternative tool for the efficient design of hydrokinetic turbine blades. As was noticed previously, the methodology corrects the chord of the blade, aiming to prevent the cavitation effect. This approach is clearly an extension of the classical Glauert's optimization, in which a correction scheme to avoid the cavitation is included on the thrust coefficient. Therefore, the present work is a simple but efficient tool, which can be helpful to those who have intention to develop technologies to the use of hydrokinetic energy. It is noteworthy that this technique can be used for hydrokinetic turbine design without major changes on the power coefficient. Furthermore, the twist angle not presents major alterations as well, because the mathematical correction influences directly the chord distribution. However, some limitations should be analyzed carefully, as following: (1) comparisons with numerical and experimental data; (2) analysis of the model at off-design condition using BET.

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REFERENCES

Batten, W. M. J., Bahaj, A. S., Molland, A. F., and Chaplin, J. R., 2008, The Prediction of the Hydrodynamic Performance of Marine Current Turbines, Renewable Energy, Vol. 33, pp. 1085-1096.

Benini, E, 2004, Significance of Blade Element Theory in Performance Prediction of Marine Propellers, Ocean Engineering, Vol. 31, pp. 957-974.

Cruz, A. G. B., Mesquita, A. L. A., and Blanco, C. J. C., 2008, Minimum Pressure Coefficient Criterion Applied in Axial-Flow Hydraulic Turbines, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 30, No. 1, pp. 30-38.

Drela, M., 1989, XFOIL: an Analysis and Design System for low Reynolds Number Airfoils. in: *Conference on Low Reynolds Number Airfoil Aerodynamics*, University of Notre Dame.

Goundar, J. N., Ahmed, M. R., and Lee, Y. H., 2012, Numerical and Experimental Studies on Hydrofoils for Marine Current Turbines, Renewable Energy, Vol. 42, pp. 173-179.

Sale, D., Jonkman, J., and Musial, W., 2009, Hydrodynamic Optimization Method and Design Code for Stall-Regulated Hydrokinetic Turbine Rotors, in: *ASME 28th International Conference on Ocean, Offshore, and Arctic Engineering Honolulu*, Hawaii.