COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1344
A NEW OPTIMIZATION PROCEDURE APPLIED TO HYDROKINETIC TURBINE SWEPT BLADES

Miriam L. A. Gemaque
Jerson R. P. Vaz
Federal University of Pará -Av. Augusto Correa, N. 1 - Belém, PA, 66075-900, Brazil
lysgmak@hotmail.com
jerson@ufpa.br
Osvaldo R. Saavedra
Federal University of Maranhão-Av. Dos Portugueses, N. 1966 – São Luís, MA, 65085-805
o.saavedra@ieee.org

Abstract. *Hydrokinetic turbine has been used worldwide for electrical generation purpose, as such a technology may strongly reduce environmental impact. Turbines designed using backward swept blades can significantly reduce axial load, being relevant for hydro turbines. However, only few works have been made in the literature on this regard. For the case of hydrokinetic rotors, backward swept blades are still challenge as the authors are unaware of any optimization procedure available, becoming this paper relevant for the current state-of-the-art. Thus, the present work develops a new optimization procedure applied to hydrokinetic turbine swept blades, being the main contribution of the approach the design of blades with reduced axial load on the rotor. The proposed method consists of an extension of the axial and blade element theories to the case of backward swept blades through a radial transformation function. As a result, such a transformation heavily affects chord and twist angle distributions along the blade, increasing the turbine torque and power coefficient.*

Keywords: *Swept Blades, Hydrokinetic Turbines, Blade Optimization.*

1. INTRODUCTION

Hydrokinetic turbines are technologies capable of converting the kinetic energy transported by rivers into electrical energy. As reported in do Rio Vaz *et al.* (2018), hydrokinetic turbines are similar to wind turbines and their efficiency is 59.3% (Betz, 1966). There are currently different types of turbines, including turbines with backward swept blades, which can significantly reduce the axial load. However, only a few studies have been done in the literature in this regard, especially for the case of hydrokinetic rotors. In this context, a novel approach for hydrodynamic optimization of hydrokinetic turbines with backward swept blades is proposed in this study. The optimization procedure is based on the Blade element momentum theory (BEMT) model for analysis of swept blade turbines.

In the work of da Silva *et al.* (2015), and presented a design of hydrokinetc turbine blades considering cavitation Therefore, a mathematical approach for design of hydrokinetic blades is presented. In which a methodology for cavitation prevention is employed.The results are compared with data from hydrokinetic turbines designed using the classical Glauert's optimization.

In the work of Muratoglu *et al.* (2021), an optimization of hydrokinetic turbines using differential evolution algorithms (DEA) was studied. The analysis was developed specifically for stall-regulated turbines, considering high hydrodynamic forces, cavitation, blade tip loss and optimal stall behavior. That paper describes a parametric study of swept blade design parameters for a 750 kW machine and how the amount of tip sweep had the largest effect on the energy production (Larwood *et al.*, 2014).

In Sessarego *et al.* (2018), a code called MIRAS is used to investigate the aerodynamic performance of winglets and sweep on horizontal axis wind turbine. The focus of the work was to carry out a preliminary study of the effect of sweep and winglets compared to straight blades in horizontal axis wind turbines. Results indicate that wind turbine blades with sweep or winglets might be better in performance compared to their straight blade. Studies indicate that the swept blade can improve the aerodynamic performance of wind turbines at low speed conditions, e.g. Zuo *et al.* (2016) present a numerical study on the effect of the swept blade on the aerodynamic performance of a wind turbine varying the tip speed ratio (TSR). After comparing and analyzing the data from the swept blade optimized with the straight blade, it was found that the power coefficient C_p of the swept blade was 3.2% higher than that of the straight blade. This shows that the swept blade optimized wind turbine can capture more energy for a high TSR.

Ding and Zhang (2016) present an ideal design method for horizontal axis turbines with swept blades. Using a 3rd order polynomial for modeling and a multiobjective algorithm, NSGA-II, for optimization, showing good behavior. Pavese *et al.* (2017) investigated the use of backward swept blades to relieve the aerodynamic load in wind turbines. Sweeping blades backward is considered an aerodynamic load-relieving technique. Slightly backward swept shapes are the best choice for the design of passively controlled wind turbines because they can achieve load relief without causing large increases in blade root torque.

Blades are the most important components of wind turbines to convert wind energy into mechanical energy. Kaya *et al.* (2018) investigated the aerodynamic performance of horizontal axis wind turbines with forward and backward swept blades, in conclusion, it was found that forward swept blades have the ability to increase performance while backward swept blades tend to decrease the coefficient of thrust, which can be important for starting the machine. Blade element momentum theory (BEMT), although conceptually simple, is still highly useful for analyzing wind turbine aerodynamics and is widely used in many design and analysis applications. Ning *et al.* (2015) analyzed the BEMT and several of the options available to assess the effect of the sloping wind direction that arrives on the rotor. In this case, BEMT proves to be quite efficient. Therefore, in the present work, we intend to develop a new model for hydrodynamic optimization of hydrokinetic turbines with backward swept blades, based on BEMT, in order to evaluate the performance gain and load reduction on the turbine rotor.

2. BLADE ELEMENT MOMENTUM THEORY FOR SWEPT BLADES

2.1 Axial momentum theory with swept radius

The axial momentum theory with swept radius, considering the rotational velocity component, is illustrated in Figure 1. In this case, the change is made only on the radial position r, which is transformed through the function.

$$\Phi\left(\frac{r}{R},\beta_i\right)=\left(\frac{r}{R}\right)^{\beta_i}. \tag{1}$$

Thus, the swept radial position r_i is taken as

$$r_i=\frac{r}{R}\Phi\left(\frac{r}{R},\beta_i\right). \tag{2}$$

where R is the radius of the turbine at the blade tip, while β_i is the local swept angle. As is well-known from the literature, there is no rotation in the wake of a conventional actuator disk, but rotation is an essential part of power extraction, in that the elemental torque, dQ, is obtained directly from the angular momentum equation applied to an infinitesimal control volume of area Figure 1, $dA = 2\pi r_i dr_i$ (Vaz and Wood, 2016).

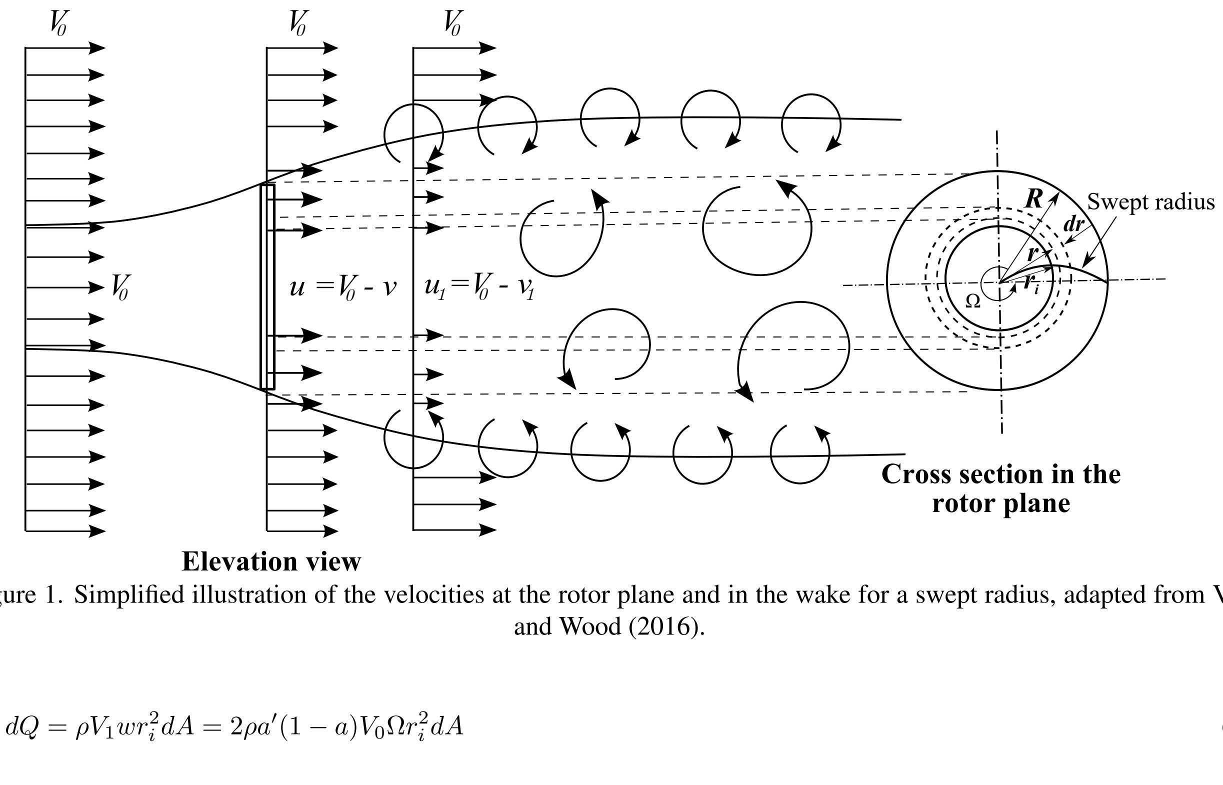


Figure 1. Simplified illustration of the velocities at the rotor plane and in the wake for a swept radius, adapted from Vaz and Wood (2016).

$$dQ=\rho V_1 w r_i^2 dA=2\rho a'(1-a)V_0\Omega r_i^2 dA \tag{3}$$

where r_i is the swept radius, $w = 2\Omega a'$ is the angular velocity in the near-wake, Ω is the rotor angular velocity, while a' and a are tangential and axial induction factors, respectively. The torque coefficient is:

$$C_Q = \frac{dQ}{\frac{1}{2}\rho V_0^2 dA} = \frac{4a'(1-a)\Omega r_i^2}{V_0} \tag{4}$$

The element power is obtained from

$$dP = \Omega dQ = 2\rho a'(1-a)V_0\Omega^2 r_i^2 dA \tag{5}$$

By integrating this expression across the rotor, the power coefficient is given by

$$C_P = \frac{P}{\frac{1}{2}\rho A V_0^3} = \frac{8}{\lambda^2}\int_0^\lambda a'(1-a)x^3 dx \tag{6}$$

Where $x = \Omega r_i / V_0$ and $\lambda = \Omega R / V_0$ are the local-speed ratio and the tip-speed ratio, respectively.

2.2 Blade element Momentum theory for turbines with swept blades

To demonstrate the BEMT analysis to turbines with swept blades, Figure 2 depicts a rotor with $N = 2$; this number is used in the figure only for convenience as the following analysis holds for any N. The transformations occur on the tangential velocity component, chord, lift and drag forces. The mathematic transformations for the radius and chord, respectively, are $r_i = \frac{r}{R}\Phi\left(\frac{r}{R}, \beta_i\right)$ and $c_i = c\cos\beta_i$, where R is the radius at the blade tip, r and c are the local radius and chord for a straight blade, while β_i is the local swept angle. The maximum swept angle at the blade tip is β, and $\beta_i = \beta/N_r$, where N_r is the number of blade elements. The transformation function at each radial position $\Phi\left(\frac{r}{R}, \beta_i\right)$ is given by Eq. (1). The following mathematical demonstrations are straightforward from BEMT analysis, where the major additional term is $\cos\beta_i$ as in Figure 2, in which the flow angle ϕ is given by:

$$\tan\phi = \frac{(1-a)\,V_0}{(1+a')\,\Omega r_i \cos\beta_i} \tag{7}$$

The relative velocity W and the bound circulation of each element,Γ,are:

$$W = \sqrt{\left[(1-a)\,V_0\right]^2 + \left[(1+a')\,\Omega r_i \cos\beta_i\right]^2} \tag{8}$$

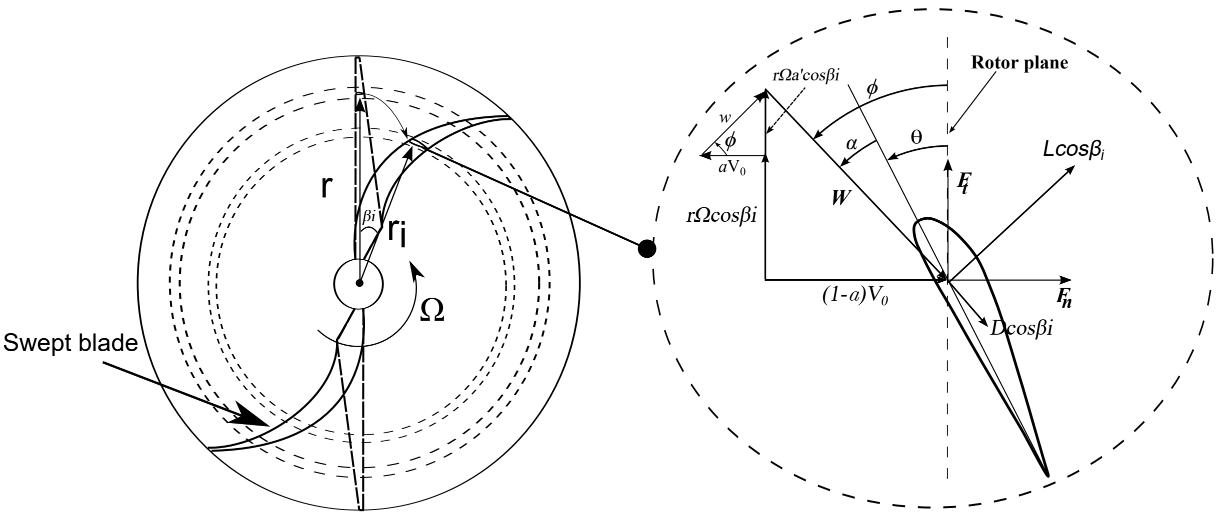


Figure 2. Simplified illustration of the variable transformations on a swept blade.

$$\Gamma = \frac{1}{2}W c_i C_l\left(1 - \frac{C_d}{C_l\tan\phi}\right) \tag{9}$$

Where C_l and C_d are the lift and drag coefficients, respectively. The normal and tangential force coefficients C_n and C_t are

$$C_n = (C_l\cos\phi + C_d\sin\phi)\cos\beta_i \tag{10}$$

And

$$C_t = (C_l \sin\phi - C_d \cos\phi)\cos\beta_i \tag{11}$$

An extended formulation for the axial and tangential flow velocities are given by:

$$\frac{a}{1+a} = \frac{\sigma_i C_n}{4F\sin\phi\cos\phi} \tag{12}$$

And

$$\frac{a'}{1+a'} = \frac{\sigma_i C_t \cos\beta_i}{4F\sin\phi\cos\phi} \tag{13}$$

Where $\sigma_i = Nc_i/(2\pi r_i)$ is the local solidity for the swept blade. Note that whether $\beta_i = 0°, c_i = c, r_i = r$ and Eq. (12) and Eq. (13) reduce to the classical Galuert expressions. The expressions for thrust and torque coefcients are

$$C_T = 2\int_{r_h}^{1}\left(\frac{W}{V_0}\right)^2 \sigma_i C_n r_i dr_i \tag{14}$$

And

$$C_Q = 2\int_{r_h}^{1}\left(\frac{W}{V_0}\right)^2 \sigma_i C_t r_i^2 dr_i \tag{15}$$

Where r_h is the radius of the hub normalized by R.The power coefcient is calculated through $C_P = \lambda C_Q$.

2.3 Optimization model for the turbine swept blade

The aerodynamic optimization is by maximizing the power coefficient through maximizing the integrand $a'(1-a)$ in Eq. (6). This requires

$$\frac{d}{da}\left[a'(1-a)\right] = \left[(1-a)\frac{da'}{da} - a'\right] = 0 \tag{16}$$

So, Equation (16) can be simplified to an equation that also applies to turbines with straight blades as used by do Rio Vaz *et al.* (2018):

$$(1-a)\frac{da'}{da} = a' \tag{17}$$

According to Hansen (2015), if the local angles of attack are below stall, a and a' are not independent since the force according to potential flow theory is perpendicular to the local velocity seen by the blade. The total induced velocity, w, must be in the same direction as the force, as illustrated in Figure 3. On the other hand, when the local angle of attack is above stall, Eq. (17) becomes invalid since the drag, which is ignored in the potential theory, becomes large. As noted by Wood (2015), Eq. (17) is only strictly true if the vortex pitch is independent of r. In particular, for $\lambda < 1$, the behavior of the induced velocity field seems to be heavily dependent on the radius. Wood (2015) showed that numerical optimization of turbines with straight blades gave constant pitch only when λ was around one or greater. Therefore, it is important to note that the present optimization procedure is valid for $\lambda > 1$ approximately, for which

$$x_i^2 a'(1+a') = a(1-a) \tag{18}$$

Where $x_i = \frac{\Omega r_i \cos\beta_i}{V_0}$. Equation (18) is derived from the angle ϕ in Figure3 in terms of

$$\tan\phi = \frac{a'\Omega r_i \cos\beta_i}{aV_0} \tag{19}$$

Equations (7) and (18) differentiated with respect to a yields

$$(1+2a')\frac{da'}{da}x_i^2 = 1-2a \tag{20}$$

If equations (17) and (20) are combined with Eq. (18), the optimum relationship between a and a' becomes:

$$a' = (1-3a)/(4a-1) \tag{21}$$

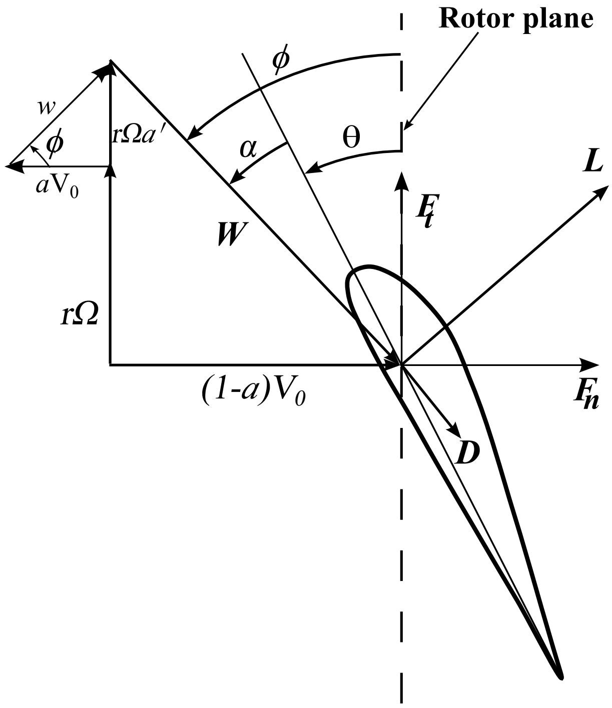


Figure 3. Velocity diagram for the section of the rotor blade.

Equation (21) was obtained by Glauert, as described by Vaz and Wood (2016) for turbines with straight blades. The optimum relationship between x_i and a can be obtained substituting Eq. (21) in Eq. (18) resulting in

$$16a^3 - 24a^2 + \left[9 - 3x_i^2\right] a + x_i^2 - 1 = 0 \tag{22}$$

Because Equation (22), the blade optimization procedure can be expressed as a function of the induction factors once the blade element lift and drag are available. So, the optimum chord and the twist angle at each blade section are calculated through the following expressions

$$c = \frac{8\pi r_i F \sin\phi \cos\phi}{BC_n} \frac{a}{1+a} \tag{23}$$

And

$$\theta = \phi - \alpha \tag{24}$$

Equation (23) comes from Eq. (12), while Eq. (24) comes direct from the velocity diagram shown in Figure3. In the high λ limit, Eq. (22) requires $a \rightarrow 1/3$, as expected even for swept blades. According to Wood (2015), as $\lambda \downarrow 0$, $a \rightarrow 1/4$, whereas the correct limit is 1/2 for an ideal turbine. This concern seems to be the same for the case of swept rotor, however further investigation is necessary. Note that the local speed ratio x_i is dependent on the local swept angle β_i, whose effect is shown in the next section.

3. RESULTS AND DISCUSSION

To analyze the performance of the proposed optimization model, the design parameters in Tab.1 are taken into account. In this case, SG6040 airfoil is used (Figure 4), considering low Reynolds number, given by $Re = \rho V_0 c/\mu$. This airfoil, according to David (2011) is one of the more modern SG aerofoils designed by Professor Michael Selig (S) and Phillipe Giguere (G) of the University of Illinios at Urbana-Champaign, specifically for small wind turbines. It is probably one of the first aerofoils designed for that purpose.

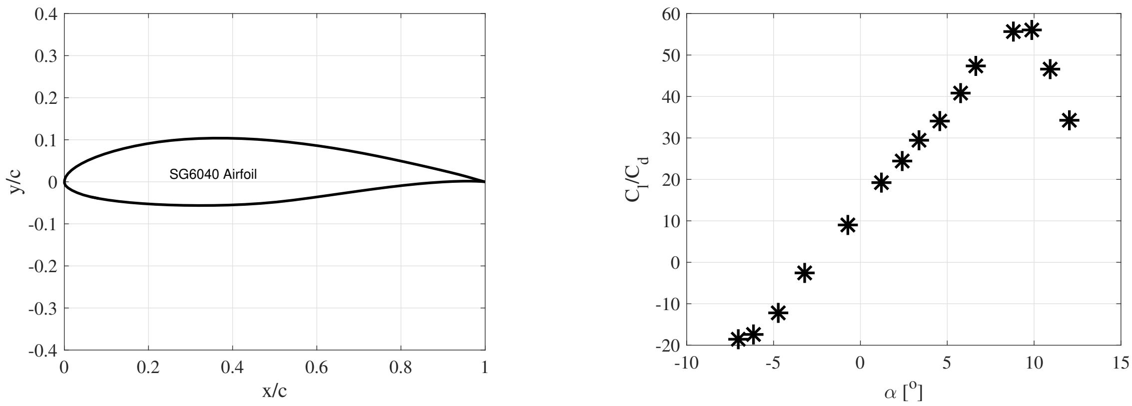
The optimum angle of attack ($\alpha = 8.8^o$) is obtained from maximum C_l/C_d ratio, whose optimum value is 56, as shown in Figure 5. The optimization procedure is done considering α constant, while the twist angle θ changes as a function of the flow angle ϕ along the blade length from Eq. (24).

Figure 5 shows the optimized chord (Figure 5a) and twist angle (Figure 5b) distributions along the turbine blade length. Note that, for the swept blade ($\beta = 30^o$), the chord heavily increases. This result is indeed interesting because larger chord distribution can avoid cavitation in hydrokinetic turbines. This subject was observed by do Rio Vaz *et al.* (2018), which developed an approach for the optimization of diffuser-augmented hydrokinetic blades free of cavitation. In their work,

Table 1. Design parameters and conditions of the turbine.

Parameters	**Value**
Turbine diameter, m	0.8
Hub diameter, m	0.08
Number of blades	4
Stream velocity, m/s	1.0
water density, kg/m^{3} (1)	997
Angular velocity, rad/s	10.5
Swept angle, degrees	30

(1) at 25 ^{o}C.

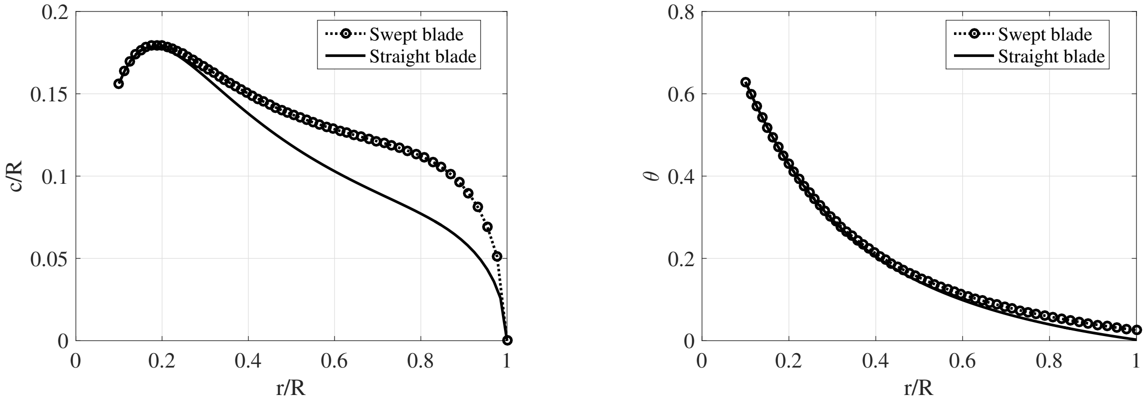


(a) (b)

Figure 4. (a) SG6040 airfoil for the section of the rotor blade. (b) C_l/C_d ratio for the SG6040 foil (Reynolds number of 150000).

to avoid cavitation, the chord distribution along the blade needs to increase as a reaction of a changing on the relative velocity approaching the rotor, in order to keep the local pressure below water vapor pressure. Here, cavitation is not evaluated, being this an assumption for a future work. However, the result demonstrates that hydrokinetic turbines doted of swept blades are really interesting in terms of hydrodynamic aspects. Torque and power coefficients of the optimized rotors for $\lambda = 4.19$ are shown in Tab. 2, considering only the optimum values of Eqs. (4) and (6). Therefore, the torque of the turbine with swept blades is about 18% higher than that with straight blades. Consequently, the power coefficient of the rotor with swept blades is also higher than for straight blades, reaching 52.9%.

Figure 6a shows a comparison of the power coefficient for both, swept and straight blades. Note that for $\lambda > 4.1$ the turbine with swept blade is more efficient. So, depending on the operating condition of the turbine it can be better to use swept blades instead straight ones. Figure 6b depicts an important result on the impact of the axial load (thrust coefficient C_T) on the rotor. The thrust is reduced for any λ. This is important because turbines with swept blades may reduce the resistive torque of the powertrain at any operating condition, contributing for a better performance of the rotor drivetrain.

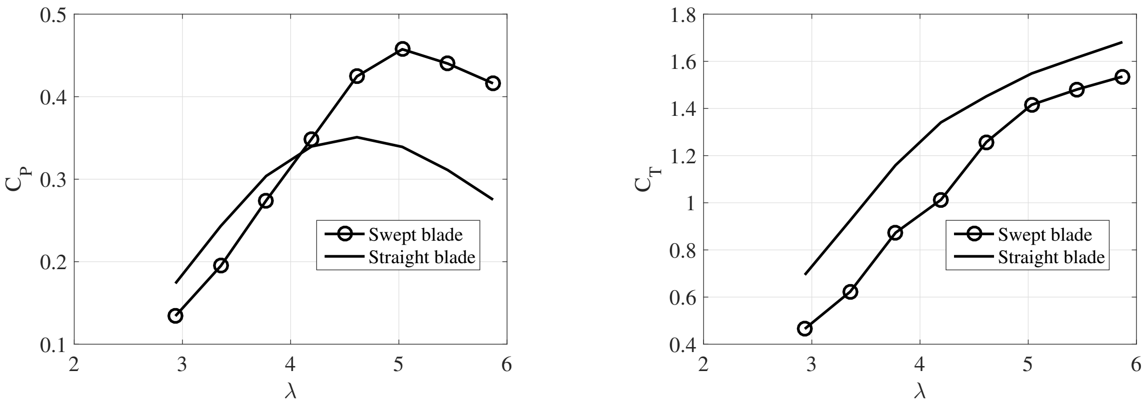


(a) (b)

Figure 5. (a) Chord and (b) twist angle distributions as functions of the radial position.

Table 2. Torque and power coefficients of the turbines.

	Swept blades	**Straight blades**
C_Q	0.13	0.11
C_P	0.529	0.46



(a) (b)

Figure 6. (a) Power and (b) thrust coeficients as functions of the tip-speed ratio λ.

4. CONCLUSIONS

This work presents a new optimization procedure applied to hydrokinetic turbines with swept blades. A comparison with an optimized hydrokinetic straight blade is performed, showing interesting results with good contributions to the current state-of-the-art. The model has low computational cost and easy numerical implementation. The proposed methodology consists of an extension of the axial and blade element theories to the case of backward swept blades through a radial transformation function. Such a transformation heavily affects chord and twist angle distributions along the blade, increasing the turbine torque and power coefficient. In the case of the torque, it can be increased about 18%. For future work, a cavitation criterion based on the minimum pressure coefficient at each blade section will be implemented, in order to assess the cavitation effect in hydrokinetic swept blades. Also, turbine performance in off-design conditions for different values of the tip speed ratio will be made.

5. ACKNOWLEDGEMENTS

The authors would like to thank the INEOF, CNPq, PROCAD/CAPES (Agreement: 88881.200549/2018-01), and PROPESP/UFPA for financial support.

6. REFERENCES

Betz, A., 1966. *Introduction to the theory of flow machines*. Elsevier.

da Silva, P.A.S.F., Shinomiya, L.D., de Oliveira, T.F., Vaz, J.R.P., Mesquita, A.L.A. and Junior, A.C.P.B., 2015. "Design of hydrokinetic turbine blades considering cavitation". *Energy Procedia*, Vol. 75, pp. 277–282.

David, W., 2011. "Small wind turbines: analysis, design, and application".

Ding, Y. and Zhang, X., 2016. "An optimal design method of swept blades for hawts". *Journal of Renewable and Sustainable Energy*, Vol. 8, No. 4, p. 043303.

do Rio Vaz, D.A., Vaz, J.R. and Silva, P.A., 2018. "An approach for the optimization of diffuser-augmented hydrokinetic blades free of cavitation". *Energy for Sustainable Development*, Vol. 45, pp. 142–149.

Hansen, M., 2015. *Aerodynamics of wind turbines*. Routledge.

Kaya, M.N., Kose, F., Ingham, D., Ma, L. and Pourkashanian, M., 2018. "Aerodynamic performance of a horizontal axis wind turbine with forward and backward swept blades". *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 176, pp. 166–173.

Larwood, S., Van Dam, C. and Schow, D., 2014. "Design studies of swept wind turbine blades". *Renewable Energy*, Vol. 71, pp. 563–571.

Muratoglu, A., Tekin, R. and Ertuğrul, Ö.F., 2021. "Hydrodynamic optimization of high-performance blade sections for stall regulated hydrokinetic turbines using differential evolution algorithm". *Ocean Engineering*, Vol. 220, p. 108389.

Ning, A., Hayman, G., Damiani, R. and Jonkman, J.M., 2015. "Development and validation of a new blade element momentum skewed-wake model within aerodyn". In *33rd Wind Energy Symposium*. p. 0215.

Pavese, C., Kim, T. and Murcia, J.P., 2017. "Design of a wind turbine swept blade through extensive load analysis". *Renewable energy*, Vol. 102, pp. 21–34.

Sessarego, M., Ramos-García, N. and Shen, W.Z., 2018. "Analysis of winglets and sweep on wind turbine blades using a lifting line vortex particle method in complex inflow conditions". In *Journal of Physics: Conference Series*. IOP Publishing, Vol. 1037, p. 022021.

Vaz, J.R. and Wood, D.H., 2016. "Aerodynamic optimization of the blades of diffuser-augmented wind turbines". *Energy Conversion and Management*, Vol. 123, pp. 35–45.

Wood, D., 2015. "Maximum wind turbine performance at low tip speed ratio". *Journal of Renewable and Sustainable Energy*, Vol. 7, No. 5, p. 053126.

Zuo, H., Liu, C., Yang, H. and Wang, F., 2016. "Numerical study on the effect of swept blade on the aerodynamic performance of wind turbine at high tip speed ratio". In *Journal of Physics: Conference Series*. IOP Publishing, Vol. 753, p. 102010.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.