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A SIMPLIFIED GENETIC ALGORITHM FOR OPTIMIZING DIFFUSER-AUGMENTED HYDROKINETIC BLADES

Marilza S. Viana
Déborah A. T. D. do Rio Vaz
Jerson R. P. Vaz
Federal University of Pará -Av. Augusto Correa, N. 1 - Belém, PA, 66075-900, Brazil
marilza182_@hotmail.com, deborah.rio@gmail.com, jerson@ufpa.br

Abstract. *The main objective of this work is to develop a simplified genetic algorithm to optimize chord and twist angle distributions of diffuser-augmented hydrokinetic turbine blades, which can also be applied to wind turbines. The methodology comprises a genetic algorithm coupled to an extended blade element momentum model, which is able to take into account diffuser effect. The approach optimizes hydrokinetic blades through maximizing turbine power coefficient, which is dependent on the axial and tangential induction factors at the rotor plane of the turbine. The proposed genetic algorithm uses the local power coefficient of the turbine as an evaluation function (fitness). Both, axial and tangential induction factors are considered in the optimization process. The main contributions of the proposed genetic algorithm are: (i) the use of a relationship between flow angle, twist angle and the angle of attack as a constraint, and (ii) the use of the blade element momentum expressions coupled into the approach, applicable to turbines with and without diffuser. The results are compared with the classical optimization method developed by Glauert, demonstrating good behavior. The proposed approach is an interesting tool for designing hydrokinetic rotors, contributing for harnessing kinetic energy from water streams.*

Keywords: *diffuser, genetic algorithm, hydrokinetic turbine.*

1. INTRODUCTION

Diffuser technology placed around hydrokinetic turbines is used to improve rotor efficiency, augmenting the flow rate throughout turbine blades. This technology has recently attained considerable attention as it shows the possibility of achieving a power coefficient that exceeds the Betz-Joukowsky limit. There is an extensive literature on the performance of diffuser-augmented wind turbines (do Rio Vaz *et al.*, 2014; Vaz and Wood, 2016, 2018). However, in the case of hydrokinetic turbines, there are still few works. For example, Gaden and Bibeau (2010) developed a numerical study to investigate the use of diffusers to improve the performance and viability of hydraulic turbines, reporting that power can increase by a factor of 3.1. Mehmood *et al.* (2012) explored various forms based on NACA-type airfoils and observed a significant increase in speed into a diffuser. do Rio Vaz *et al.* (2018) propose an optimized model based on the Blade Element Momentum (BEM) theory. In their work, they take into account the influence of the diffuser speed-up ratio regarding cavitation effect. A changing on the thrust coefficient is assumed to optimize chord and twist angle distributions along the blade. These works demonstrate the importance of maximizing power through optimizing turbine blades.

In this context, the present paper proposes a simplified genetic algorithm (GA) to optimize hydrokinetic blades. The optimization based on GAs consists on the search for the best solution for a given problem. It consists of trying various solutions and using the information obtained in this process in order to find increasingly better solutions. The first step in a typical GA is the generation of an initial population of chromosomes, which is formed by a random set of chromosomes that represent possible solutions to the problem to be solved. During the evolutionary process, this population is evaluated and each chromosome receives a score, reflecting the quality of the solution it represents. Therefore, in the present work, a GA model is developed, which is applied to the optimization of hydrokinetic blades. The approach maximizes the local turbine power coefficient using BEM theory, which is dependent on the axial and tangential induction factors at the rotor plane. The approach uses the local power coefficient as an evaluation function (fitness). The results are compared with the classical optimization method developed by Glauert (1935), proving to be satisfactory, suggesting that the turbine

mechanical power can increase about 66% for a rated water velocity of 2.5 m/s when compared to the turbine designed using Glauert's optimization without diffuser.

2. OPTIMIZATION PROCEDURE USING GENETIC ALGORITHM

The approach via genetic algorithms uses the expressions of the BEM model extended to the case of turbines with diffusers, according to the model described in do Rio Vaz *et al.* (2018). BEM expressions are used in order to consider the local power coefficient as the fitness into GA model, imposing a constraint based on the velocity diagram at each blade section, granting the stabilization during GA searching. For this, the following relationship is considered for the calculation of the axial induction factor, a, for a turbine with diffuser:

$$\frac{a}{1-a} = \frac{\gamma^2 \sigma C_n}{4 \sin^2 \phi}$$
(1)

where γ is the diffuser velocity ratio without rotor, as illustrated in Fig. 1. C_n is the normal force coefficient on each blade section, ϕ is the flow angle, and σ is the local solidity, given by

$$\sigma = \frac{Bc}{2\pi r}$$
(2)

where B is the number of blades and c is the chord at each blade section. The tangential induction factor is determined using

$$\frac{a'}{1+a'} = \frac{\sigma C_t}{4 \sin \phi \cos \phi}$$
(3)

To calculate the fitness of the proposed GA, the local power coefficient is considered as (do Rio Vaz *et al.*, 2018):

$$dCp = \frac{8}{\lambda^2} \gamma a' (1-a) x^3 dx$$
(4)

Note that, integrating Eq. (4), yields

$$Cp = \frac{8}{\lambda^2} \int_0^\lambda \gamma a' (1-a) x^3 dx$$
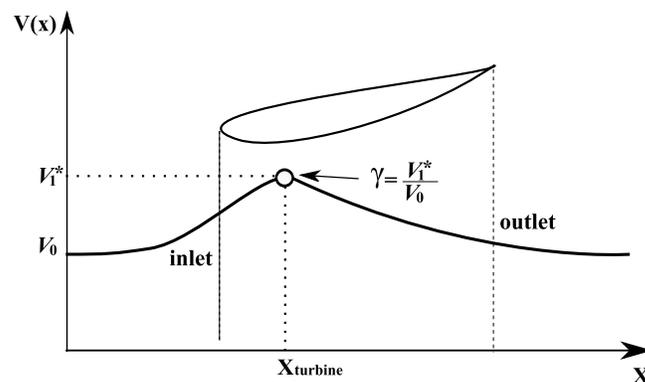(5)

Figure 1. Illustration of the diffuser velocity ratio on the symmetry axis of a diffuser without turbine (do Rio Vaz *et al.*, 2014).

The local power coefficient, dCp, corresponds to a cubic function of the local-speed ratio, x, with a well-defined maximum point (optimal point of the curve). Therefore, the proposed GA seeks the optimum point of the dCp curve. It is worthy noting that the maximum value of Cp, given by Eq. (5) is exactly the Betz-Joukowsky limit if $\gamma = 1$. The numerical scheme aims to find the best chord, c, and the best twist angle, β (for a given operating condition) in such a way that C_p is always the maximum (flow chart in Fig. 2). The diffuser velocity ratio, γ, the axial induction factor, a, and the tangential induction factor, a', are all dependent on the radial position. This fact contributes to allow GA model to search
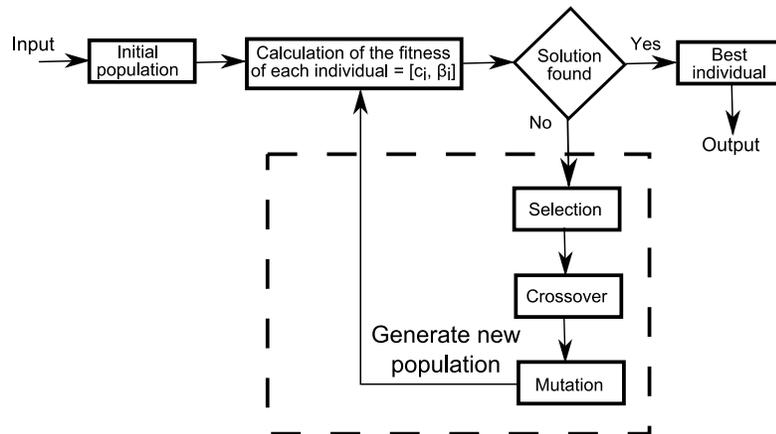
Figure 2. Flow chart of the genetic algorithm.

for the best blade geometry, composing an optimized hydrodynamic turbine. Here, γ for simplicity will be considered radially constant.

The main difference of the present GA approach is the use of a constraint based on the velocity diagram of each blade section, as illustrated in Fig. 3. This allows the BEM model to be coupled with GA, becoming it an interesting approach to optimize hydrokinetic rotor. In this case, the constraint is given by the relationship between the angles formed on the blade section. Through Fig. 3, the flow angle is always, along the entire blade, the sum of the angle of attack and the twist angle, as

$$\phi = \alpha + \beta \tag{6}$$

Hence, the proposed GA model searches for the best β, keeping Eq. (6) true for each blade section. Similarly, the best chord is searched by the GA to optimize the power coefficient, Cp, in Eq. (5). This occurs through Eq. (2) combined with Eqs. (1) and (3). All the design parameters used to verify the performance of the proposed GA approach is presented in the next section.
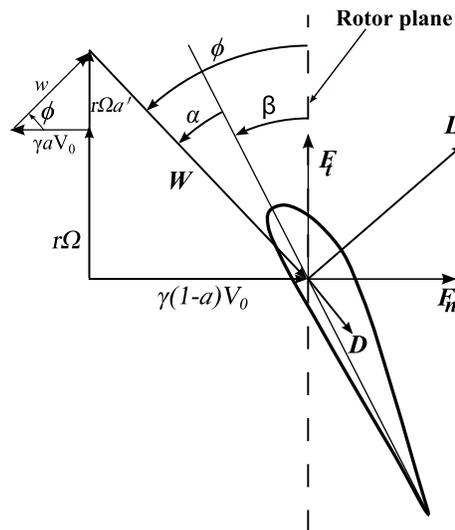

Figure 3. Velocity diagram for each section of the rotor blade (Vaz and Wood, 2016; do Rio Vaz *et al.*, 2018).

3. RESULTS AND DISCUSSION

3.1 The simulated hydrokinetic turbine

To analyze the performance of the proposed GA model, it is considered the horizontal axis hydrokinetic turbine described in Tab. 1. For the turbine blades, the hydrofoil NACA $65_3 - 618$ is used, and its hydrodynamic parameters such as lift, drag, and minimum pressure coefficients are obtained by the free software XFOIL (Drela, 1989), which is a coupled panel/viscous code developed at MIT. According to do Rio Vaz *et al.* (2018), 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 hydro and hydrodynamic design, and presenting good agreement when compared with experimental data (Favacho *et al.*, 2016; Silva *et al.*, 2018).

For the GA model, the "gaoptimset" function from MATLAB was used. Tab. 2 shows the GA algorithm parameters used in the design of the hydrokinetic blades. In this case, the parameter "EliteCount" is the number of best individuals that survive to next generation without any change. The crossover function used is the "crossoverintermediate", which creates children by taking a weighted average of the parents. The weights can be specified by a single parameter, Ratio, which can be a scalar or a row vector of length "Number of Variables". The default is a vector of all 1's. The function creates the child from $parent_1$ and $parent_2$ using the following formula:

$$\text{child} = \text{parent}_1 + \text{rand} \times \text{Ratio} \times (\text{parent}_2 - \text{parent}_1) \tag{7}$$

In the present work, the default "Ratio" is considered. The mutation function used is "mutationadaptfeasible". Such a function is used when there are constraints, through which randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. The mutation chooses a direction and step length that satisfies bounds and linear constraints.

Table 1. Design parameters and operating condition of the hydrokinetic turbine.

Parameters	Values
Turbine Diameter (D)	10.0 m
Hub Diameter	1.5 m
Number of blades	3
Free-stream Velocity (V_0)	2.5 m/s
Water density $(\rho)^{(1)}$	997 kg/m^3
Angular velocity (Ω)	35 rpm

$^{(1)}$ measured at 25^oC

Table 2. Design parameters for the GA model.

Parameters	Values/Description
Population size	30
Lower and upper bounds to c	[0, 1] in meter
Lower and upper bounds to β	[-5, 50] in degrees
Generations	10
Number of variables	2
EliteCount	4

3.2 Results of the proposed genetic algorithm

To assess the behavior of the proposed GA, a comparison is made with the classical optimization model developed by Glauert (1935). The design conditions are the same as those described in Tab. 1. Fig. 4 shows the results obtained for the optimized chord and twist angle distributions for $\gamma = \{1.0, 1.3, 1.6\}$. Note that the results using the GA model presents chord distribution different from that using Glauert's optimization only close to the blade root for any γ (Fig. 4a), while

the twist angle distribution is strongly affected by the diffuser. Increasing γ, the twist angle increases as well, changing the aerodynamic performance of the turbine. This occurs because the search performed by the GA model always aims to reach the maximum point of the local power coefficient, as shown through the fitness behavior in Fig. 5. In this case, Glauert's optimal model presents a local power coefficient non linear, while GA presents a linear behavior for dCp. These behaviors demonstrate that the new aerodynamic geometry of the blade using GA is interesting to be further studied, as it differs from that commonly used in the literature (Glauert, 1935). The non linear behavior in the calculation of dCp using Glauert's optimization occurs due to the dependence of the performance parameters on the induction factors at the blade typically found in iterative models based on the BEM theory. These results show that the GA model works very well with BEM, even considering a strong diffuser effect.

Fig. 6 shows the performances of the optimized rotors with and without diffuser. The difference observed on the chord distribution close to the blade root (Fig. 4a) does not cause that much change on the turbine power coefficient, as depicted in Fig. 6a, which demonstrates same turbine efficiency for both rotors, Glauert and GA (for $\gamma = 1$). However, for the cases of $\gamma = 1.3$ and 1.6, the turbine efficiency substantially increases. This is because the twist angle distribution is heavily affected by the increasing on γ. Also, the diffuser changes the operational condition from which the power coefficient is maximum. For the case without diffuser ($\gamma = 1$), the tip-speed ratio is 11.4, while for $\gamma = 1.6$ the tip-speed ratio becomes 9.61. This change occurs because the diffuser modifies the flow passing through the turbine rotor, changing mainly the axial velocity. Fig. 6b shows that the turbine mechanical power can increase about 66% for the rated water velocity of 2.5 m/s when compared to the Glauert's optimization.

Usually, GA models are time-consuming, as described by Silva *et al.* (2017), which performed a comparison with $HARP_{opt}$ code (Sale, 2010), a multiple objective genetic algorithm associated to BEM theory applied to design horizontal axis wind and hydrokinetic turbine rotors. The main difference between the present GA approach and $HARP_{opt}$ code, is that to limit the variables needed to completely define the blade geometry, Bezier curves are fit through control points within $HARP_{opt}$ code. These control points make the code more stabilized, but time-consuming. This is not necessary in the present approach, as the constraint through Eq. (6), apparently can grantee the stabilization of chord and twist angle distributions during GA searching. In the comparison made by Silva *et al.* (2017), $HARP_{opt}$ spent more than 2 h, while in all simulations carried out here the computational time does not exceed 121 s. Another important difference is that the present GA model is applied for both turbines, with and without diffuser, while $HARP_{opt}$ code is applied only for turbines without diffuser. However, $HARP_{opt}$ includes a cavitation constraint, which is indeed important for hydrokinetic turbine design. The implementation of a correction to avoid cavitation inception is the next step of the present work, including the effect of tip loss. This effect is really important considering optimization procedures. Also, the radii variation of the diffuser velocity ratio, γ, will be considered in the next version of the present GA code. Probably, the γ radii variation will contribute to a change on the chord distribution, as the axial velocity close to the blade tip for a shrouded turbine generally is higher than at the blade root.

The present work is an initial study of an alternative model, coupling GA with BEM, being an interesting tool for optimizing wind and hydrokinetic turbine blades with and without diffuser. The first results demonstrate good performance of the proposed model, which can also be extended in the future to a multiple objective genetic algorithm. Multiple objective optimization is able to maximize the turbine's annual energy production, which is calculated using a Rayleigh, Weibull, or other defined flow distribution. Additionally, maximum power point tracking can be a combined objective with annual energy production, becoming the GA modeling a powerful tool for wind and hydrokinetic design.

4. CONCLUSIONS

This work shows an efficient GA model applied to the optimization of wind and hydrokinetic blades. The GA model is coupled to the BEM, through which a constrain based on the velocity diagram for the section of the rotor blade is employed. The results show that chord and twist angle distributions are different from that determined by using Glauert's optimization, mainly for the twist angle distribution, presenting high variation under diffuser effect. Close to the blade root, the chord distribution is lower than that obtained by Glauert's optimization, even when the diffuser effect is strong. Compared with other models available in the literature, the constraint based on the velocity diagram seems to stabilize the GA code, being a good alternative, as generally models available use Bezier curves, which can be time-consuming.

It is necessary to consider some limitations of the present model, such as a strategy to implement a correction to avoid the cavitation effect, as well as the implementation of a tip loss formulation. Despite such limitations, the results obtained in this work present physically consistent behavior, showing that the GA model is an alternative to be extended to a multiple objective genetic algorithm including diffuser effect, which produces a significant increase in the power coefficient, justifying the use of diffusers as a technology to increase wind and hydrokinetic turbine power output.
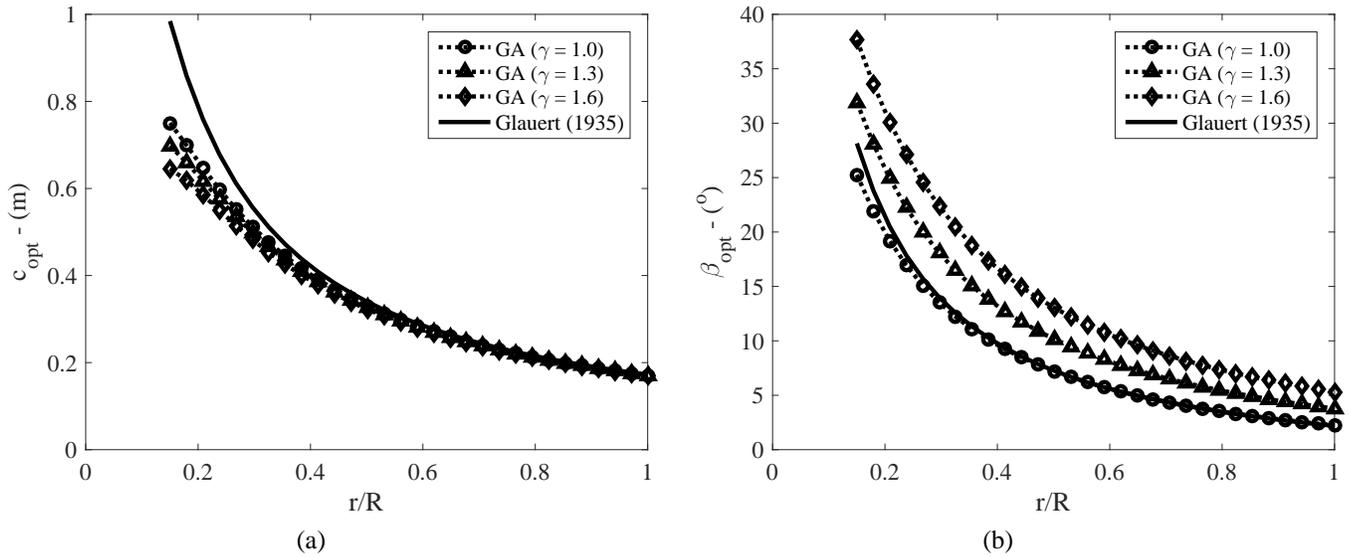
(a)

(b)

Figure 4. Optimized blade geometries for $\gamma = \{1.0, 1.3, 1.6\}$: (a) chord, c_{opt}, and (b) twist, β_{opt}, distributions.

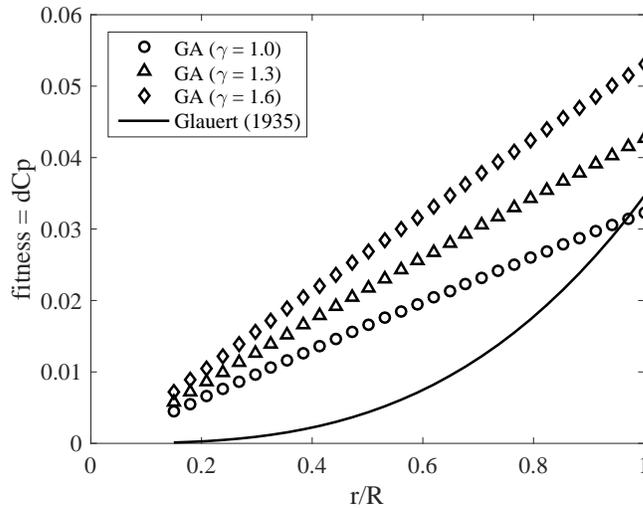Figure 5. Calculated fitness, Cp_{opt}, for $\gamma = \{1.0, 1.3, 1.6\}$.

5. ACKNOWLEDGEMENTS

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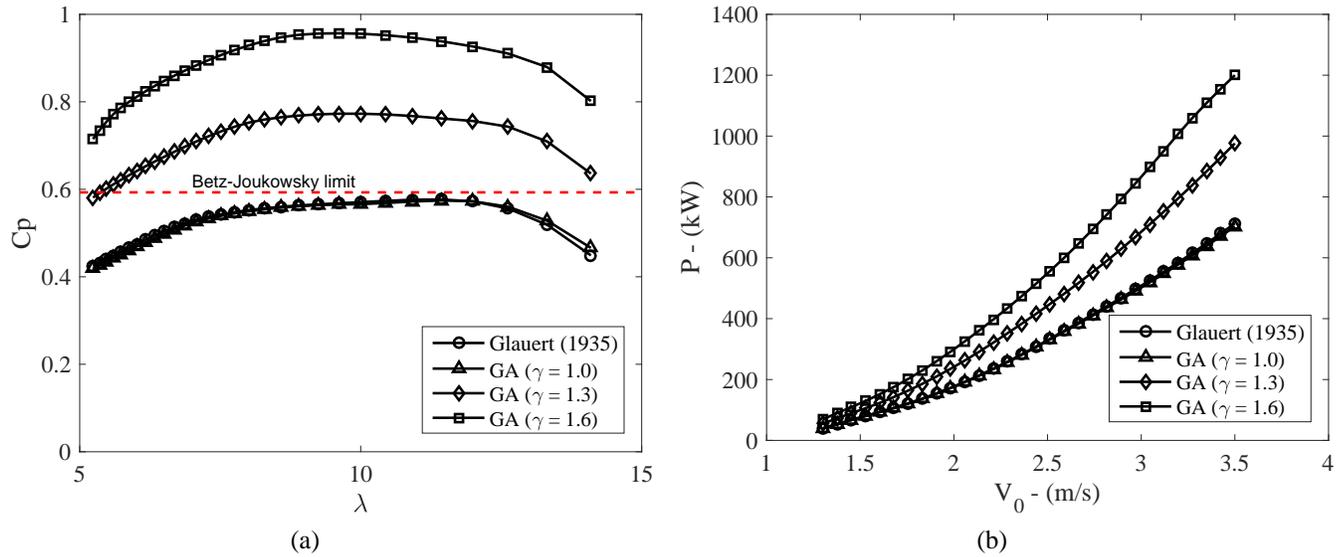
Figure 6. (a) Power coefficient, and (b) Mechanical power.

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