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**SCREENING ANALYSIS AND UNCONSTRAINED OPTIMIZATION OF A SMALL-
SCALE VERTICAL-AXIS WIND TURBINE**

Ilha Solteira, 2021

PEDRO FRANCISCO SILVA TRENTIN

**SCREENING ANALYSIS AND UNCONSTRAINED OPTIMIZATION OF A SMALL-
SCALE VERTICAL-AXIS WIND TURBINE**

Course completion paper presented to the School of Engineering at Ilha Solteira - Unesp as part of the requirements for obtaining the title of Bachelor of Sciences in Mechanical Engineering.

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Ao trigésimo dia do mês de Junho de dois mil e vinte, às dezesseis horas, em reunião pelo Google Meeting (<https://meet.google.com/tqo-xebt-ynp>), o discente PEDRO FRANCISCO SILVA TRENTIN, matriculado sob o RA 162053861, apresentou o Trabalho de Graduação intitulado SCREENING ANALYSIS AND UNCONSTRAINED OPTIMIZATION OF A SMALL-SCALE VERTICAL WIND TURBINE, tendo como banca examinadora o PROF. DR. LEANDRO OLIVEIRA SALVIANO (Orientador/Presidente), PROF. DR. ALUISIO VIAIS PANTALEÃO, PROF. MSC. GABRIEL BERTACCO DOS SANTOS. Após exposição e arguição, o discente foi **APROVADO** pela Comissão Examinadora. Encerrada as atividades, lavro a presente Ata.

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Discente:

Pedro Francisco Silva Trentin



Ilha Solteira, 30 de Junho de 2021.

To my parents.

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“Discipline is the mother of success”
Ésquilo (525 a.C – 456 a.C)

ABSTRACT

The demand for alternative and renewable energy sources has been growing substantially in recent years due, among other things, to the economic and environmental aspects of conventional sources, such as oil and its derivatives. In this context, wind energy has emerged as an attractive renewable source, envisioning the possibility of developing new technologies and more efficient equipment to meet energy needs. In this work, computational modeling was performed through Computational Fluid Dynamics (CFD) of a small Darrieus vertical axis wind turbine (VAWT) at tip-speed ratio (λ) = 2.63 coupled to an optimization algorithm and a response surface (RS) methodology to find a optimal VAWT considering the impact of four geometric parameters: number of blades (N), chord length of the airfoil (c), diameter (D), and pitch angle (β). For the numerical model, a two-dimensional, incompressible, turbulent and unsteady-state flow is considered. Moreover, after a robust numerical validation procedure, a sensitivity analysis (SA) was performed using the Morris method to identify the influence of each geometrical variable on the turbine performance, revealing that the contribution index of the pitch angle (β) is the highest among all the parameters (58%). From the same design of experiment (DoE) used by SA, a RS was trained to perform an optimization process using the NSGA-II method, increasing the conversion efficiency by 40%. A detailed discussion is presented related to flow dynamics considering the impact of each variable on the power coefficient. The strategy adopted here, in which a qualitative sensitivity analysis is associated with a response surface and an unconstrained optimization, was shown to be robust and can be applied to high-dimensional and computational-expensive CFD models to reduce computational costs with adequate results regarding fluid flow phenomena.

Keywords: Small-Scale Wind Turbine, Numerical Modeling, Optimization, Sensitivity Analysis.

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1. INTRODUCTION

Global warming, energy scarcity, possible rising of prices and depletion of fossil fuels, and exponential growth in energy demand in several countries have created an excellent opportunity for large-scale acceptance of renewable energy technology [1], increasing the pressure on conventional energy sources and their misfortunes. Worldwide, the share of renewable energy will increase to address global climate changes by 2030 [2]. In this scenario, the kinetic energy resulting from air currents (wind) has been an important source of energy due to its capacity for renewal and sustainability. The growth of wind energy production in the world envisions possibilities for the development of new technologies and more efficient equipment, in terms of both large and small scale [2].

Wind energy refers to the process of generating electricity using wind or airflow that occurs naturally in the Earth's atmosphere. Wind turbines are equipment that converts the kinetic energy of wind into mechanical energy and later into electricity through an electric generator. Current wind turbines can be classified into two types based on axis orientation: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) [3]. While HAWTs (Figure 1(a)) continue to be commercially viable for large-scale energy production, VAWTs (Figure 1b-c) operate under low wind speeds conditions that are favorable for a small-scale generation. As a whole, VAWTs have recently received a growing interest in power generation for the urban environment [4,5]. This increase in interest is due to some advantages, such as: considerably low TSR (Tip Speed Ratio) operation, omnidirectional capacity (no yaw system used to control the position of the wind turbine rotor in relation to wind direction), low noise emission, lower manufacturing cost, low installation and maintenance cost (due to the generator being on the ground or at small heights) and attractive visual [6].

According to the principles of aerodynamics, small VAWTs can be classified into drag-based turbines and lift-based turbines [7]. The Savonius turbines (Figure 1(b)) are wind turbines based essentially on drag force, and its shape is similar to "spoons" (as the blades are called due to the cross-section feature in "S"). The Darrieus wind turbine (Figure 1(c)) is a lift-based turbine. This type of wind turbine was designed by Georges Jean Marie Darrieus in 1931 [8].

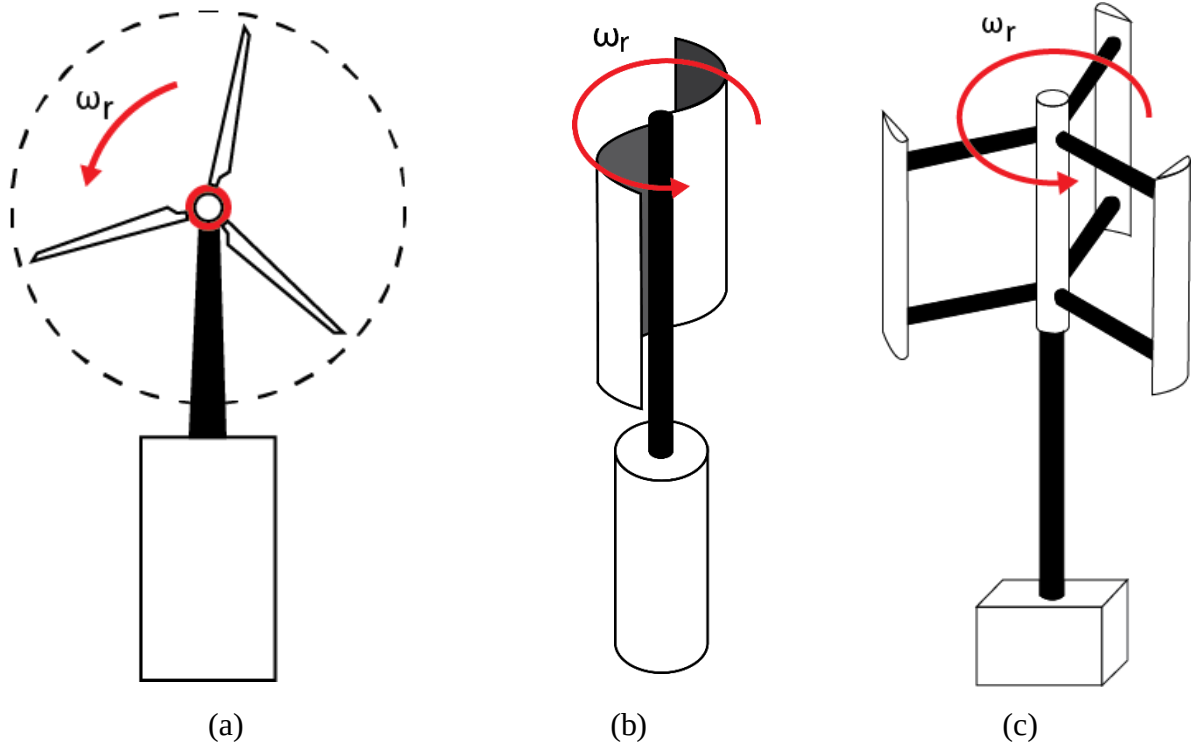


Figure 1. Wind Turbines: (a) HAWT; (b) VAWT Savonius; (c) VAWT Darrieus.

Increasing studies are being done to improve the efficiency and to extend the applicability of wind turbines to all suitable locations [9] through experimental and numerical approaches. Several numerical simulation techniques have been developed, among which the Blade Element Momentum (BEM) and Computational Fluid Dynamics (CFD) can be highlighted. The application of CFD simulation has proven to be an excellent option for analysis and decision making, playing a fundamental role for the development of new technologies in wind energy, helping to design more efficient and productive wind turbines [10], although BEM methodology can also provide important insight.

The power generation performance of Darrieus VAWTs has been investigated by several works due to the different parameters such as rotor diameter, chord length, solidity, TSR(Tip-Speed Ratio), blade profile, blade height, pitch angle and number of blades [10]. Castelli et al. [11] investigated the aerodynamic performance of a Darrieus VAWT for different conditions. A two-dimensional simulation was proposed, and the authors recommend that the NACA 0021 three-blade rotor was the best configuration. Balduzzi et al. [12] introduced a CFD model, selecting and identifying the different model parameters for the Darrieus 2D turbine simulations. This model was used to simulate a rotor and to compare the results with the experimental data. A remarkable agreement was observed between numerical results and experimental data. Strickland et al. [13] conducted experiments to investigate the effect of

increased solidity on VAWTs near-wake structure and concluded that to maximize the efficiency of VAWT a balance between solidity, TSR and the magnitude of the flow blocking effect should be achieved [14]. Sabaeifard et al. [15] presented an experimental and computational investigation to perform the aerodynamic performance of Darrieus VAWT with straight blades, due to solidity, number of blades and cross-section of the airfoil. The results of this study indicated an optimal configuration in which the highest C_p are 0.32 and 0.36 for the experimental and CFD calculation, respectively.

Moreover, the number of blades has a significant effect on overall torque. The larger the number of blades, the lower the angular speed that achieves the higher power coefficient. On the other hand, the lower the number of blades, the higher the angular speed that achieves the highest performance [16]. From the structural design point of view, it is advantageous to have few large-chord blades instead of many small-chord blades, since the bending stiffness of the blade increases quadratically with the blade chord, while aerodynamic loads increase proportionally [17]. On the other hand, VAWTs self-start capacity improves as the number of blades increases [18]. Some studies indicate that the three-blade turbine will self-start, while the two-blade turbine will only self-start in some azimuthal positions [19,20].

The blade pitch angle (β) is another important parameter that impacts the VAWT performance. This angle is subtended between the blade chord and a reference line which is parallel to the incident wind, as shown in Figure 3. A neutral blade pitch angle ($\beta = 0^\circ$) occurs when the blade chord and tangent line are collinear. Positive pitch angles ($\beta > 0^\circ$) are defined as an internal rotation of the blade toward the turbine rotation axis. In the other case, the negative pitch angles ($\beta < 0^\circ$) are facing the front edge of the blade away from the axis of rotation [14]. Klimas and Worstell [21] were the first researchers to examine the influence of the blade pitch angle on VAWT performance. It was identified that small angles of negative inclination improved performance with the maximum power coefficient at $\beta = -2^\circ$. On the other hand, positive inclination angles deteriorated the global efficiency. It is important to note that high pitch angles ($\beta = \pm 6^\circ$) are harmful to the performance and also can cause a severe load imbalance between the blades. Rezaeiha et al. [22] showed that the power coefficient increased by 6.6% using a pitch angle of $\beta = -2^\circ$ and that the wind turbine performance is considerably more sensitive to positive pitch angles rather than negative pitch angles. Chen and Zhou [23] evaluated the aerodynamic performance of a VAWT considering pitch angles in the range of -5° to 5° for a two-dimensional analysis with three blades and NACA0018 profile. They showed that the power coefficient increased slightly between -5° and -2° . Sumantraa et al. [24] also analyzed the effect of pitch angle on the performance of a VAWT for three-pitch angles, 6° , 0°

and -6° . The authors concluded that the best performance occurred for $\beta = -6^\circ$ for all TSR investigated.

Therefore, former works have provided a traditional analysis of the main geometrical parameters of VAWT, such as chord, pitch angle, blade shape and number of blades. However, a sensitivity analysis (SA) through a statistical tool applied to investigate the impact of the geometrical parameters on VAWT performance still lacks in the literature. A description of the importance of each input towards an interesting output can be provided by the appropriate SA method. Among the many options available, from the screening qualitative to the variance-based quantitative methods, [25] the elementary effects (EE) method introduced by Morris [26] and refined by Campolongo et al. [27] is considered a good practice in qualitative SA. Highly cost CFD models, similar to those found in unsteady and turbulent flow through a wind turbine, can benefit from this screening method that seeks to identify non-influential input variables using a relative small number of original model evaluations. This method has been widely used in different areas of science, such as pasture simulation [28], centrifugal compressor [29] and controllers applied to water treatment plants [30]. However, this method has not yet been applied to numerical simulations of wind turbines.

Besides of being an important tool to find the main geometrical parameters that impact VAWT performance, SA could also contribute to an optimization procedure since non-important geometrical parameters could be fixed in the analysis, which increases the convergence speed, assisting to find optimal solutions. In most cases, the optimization procedure applied to wind energy conversion systems involves the maximization of wind turbine performance. Bedon et. al. [31] developed a computational algorithm called W.O.M.B.A.T. (Weatherly Optimization Method for Blades of Air Turbines) based on Genetic Algorithm. The authors used the airfoil thickness and chord as input variables, and reported an optimal profile that increased the VAWT efficiency by 1.8%. Chen et. al [32] utilized an heuristic search algorithm, the Covariance Matrix Adaptation Evolutionary Strategy (CMAES), where three geometrical variables of the rotor were modified (turbine radius, the ratio of radius over half-height and blade number). Moreover, to validate the optimization output, a 3D CFD simulation was conducted, showing a satisfactory agreement between the optimized model and the numerical output.

Overall, a promising approach to find optimal wind turbine design is the coupling of sensitivity analysis methodology and optimization algorithm for computationally expensive modeling. Thus, the present work uses an interesting strategy, combining SA effective screening method and an optimization procedure based on Response Surface Methodology

(RSM), considering a two-dimensional computational model of a small-scale Darrieus VAWT. The coefficient of performance (C_p) of the VAWT is investigated as a function of geometric characteristics: number of blades (N), profile chord length (c), turbine diameter (D) and pitch angle (β) at $TSR = 2.63$. These are parameterized as input variables to be evaluated by the Morris method and the same DoE used for this qualitative screening analysis is applied to RSM training. Following, the trained response surface is also used for the optimization procedure and for the convergence study of Morris sensitivity measures. This strategy accelerates the optimization of the VAWT design.

2. METHODOLOGY

A strategy, similar to presented by Salviano et al. [29], is proposed here (see Figure 2). It starts with the CFD modeling using ANSYS DesignModeler software in which the first geometry of the Darrieus VAWT is generated based on the geometrical parameters considered by Castelli et.al [11]. The ANSYS Meshing software is used to discretize a computational domain. A grid independence study is then performed following the Grid Convergence Index (GCI) method [33], a robust method to study the mesh density. If the GCI index is satisfactory, a numerical validation is performed from experimental data [11]. Furthermore, the verified CFD model is submitted to an input variables range definition in order to start a sequential sensitivity analysis. A quasi-optimal sampling [34] design of experiment (DOE) is defined to maximize the distance between Morris trajectories for better screening in Morris method of sensitivity analysis [26] and also for RS training, according to Salviano et al. [29]. Additional cases are created by the uniform Latin Hypercube Sampling (LHS) method [35] to increase the response surface quality. Morris sensitivity measures are taken for factor ranking, which robustness of the results is verified through trajectory number extrapolation. Finally, the optimal VAWT design found by the optimization procedure is verified by the CFD model, and the dynamic flow phenomenology of the optimal design is discussed in detail.

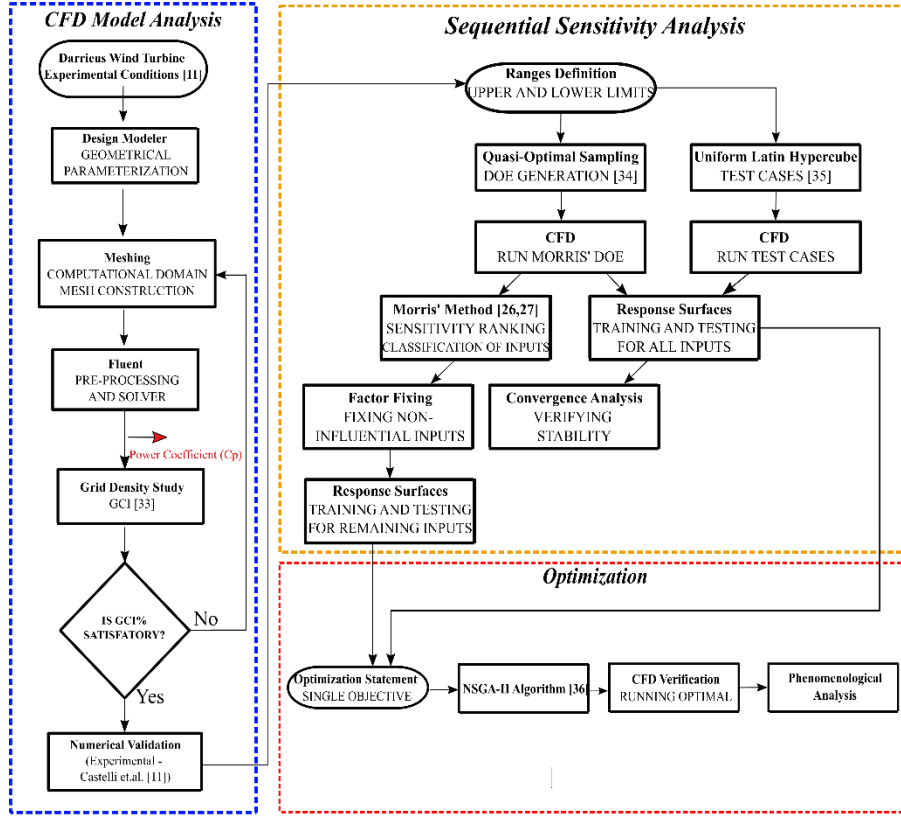


Figure 2. Adapted flowchart from Salviano et al. [29] showing the complete methodology of CFD, Sequential Sensitivity Analysis and Optimization.

2.1. AERODYNAMICS OF DARRIEUS WIND TURBINES

The phenomenological aspects of airflow through VAWT can be much more complex compared to HAWT, this is attributed to unstable power conversion due to large variations in the pitch angle and relative speed of the turbine during each revolution [36]. Torque is produced from the airflow over the blade profile of the wind turbine. As in any rotating profile in turbomachinery, a speed triangle is generated at the azimuthal position (θ), as shown in Figure 3. The wind incidence velocity U_∞ results in a local velocity at the blade U_{local} which, together with the VAWT rotation, generates a circular motion of the blade. This local velocity U_{local} can be decomposed into two components, tangential velocity and normal velocity on the aerodynamic profile, as shown in Equations (1) and (2) [37].

$$U_T = \omega_r R - U_{local} \sin \theta \quad (1)$$

$$U_N = U_{local} \cos \theta \quad (2)$$

The effective velocity U_{eff} is given by Equation (3).

$$U_{eff} = \sqrt{U_T^2 + U_N^2} \quad (3)$$

According to the dynamic flow over the blades of a Darrieus VAWT, a drag force (F_D) in the direction of free stream, and a lift force (F_L) normal to the free stream are generated. These forces are variable and dependent on the incidence of the airflow as well as the angle of attack α , which depends on azimuthal position (θ), as shown in Equation (4) [38]. However, torque can be better expressed by decomposing the forces into normal (F_N) (Eq. (5)) and tangential (F_T) (Eq. (6)) components [39], as shown in Figure 3.

$$\alpha = \tan^{-1} \left[\frac{\sin \theta}{\lambda + \cos \theta} \right] \quad (4)$$

$$F_N = F_L \cos \alpha + F_D \sin \alpha \quad (5)$$

$$F_T = F_L \sin \alpha + F_D \cos \alpha \quad (6)$$

Thus, the lift coefficient (C_l) and drag coefficient (C_d) can be computed as [40]:

$$C_l = \frac{F_L}{\frac{1}{2} \rho U_\infty^2 A} \quad (7)$$

$$C_d = \frac{F_D}{\frac{1}{2} \rho U_\infty^2 A} \quad (8)$$

Finally, the power coefficient (C_p), Equation (11), of a Darrieus VAWT can be computed using the torque coefficient (Equation (9)) and the TSR (Equation (10)), according to Mohamed [38]. The solidity parameter is given by Equation (12) [14].

$$C_t = \frac{T}{\frac{1}{2}\rho ARU_\infty^2} \quad (9)$$

$$\lambda = \frac{\omega_r R}{U_\infty} \quad (10)$$

$$C_p = \lambda C_t \quad (11)$$

$$\sigma = \frac{Nc}{R} \quad (12)$$

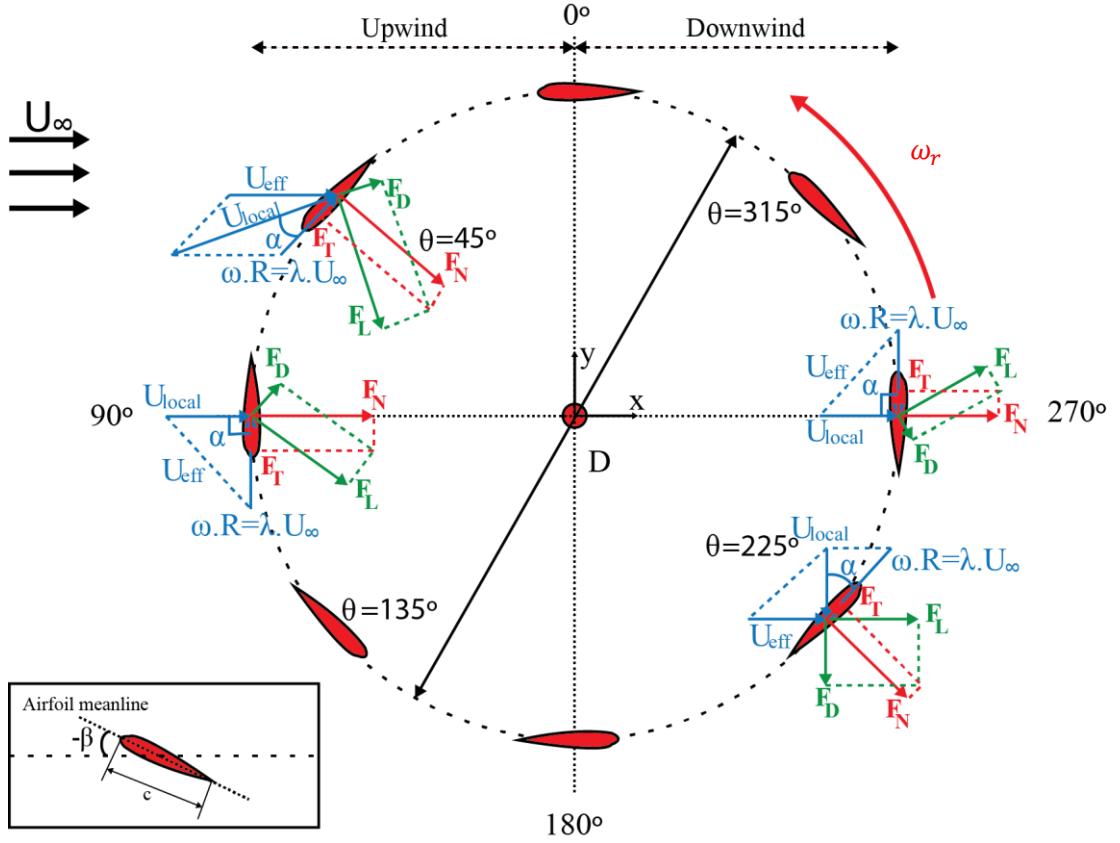


Figure 3. 2D representation of a VAWT showing the aerodynamic forces, velocities, and incident angles.

2.2. GOVERNING EQUATIONS

For modeling the fluid flow dynamics through the Darrieus VAWT, the Unsteady Reynolds-Averaged Navier-Stokes (URANS) approach is adapted using the Coupled algorithm

for the pressure-velocity coupling [39,41]. The discretization is performed using the Finite Volume Methodology, considering the assumptions of two-dimensional, incompressible, turbulent and unsteady flow. These assumptions are suitable for modeling the flow dynamics according to BAI et al. [42], and the numerical solution is performed using commercial software ANSYS Fluent 19.0.

Thus, the continuity and momentum equations can be presented as shown by Equation (13) and Equation (14), respectively.

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_i} = 0 \quad (13)$$

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} - \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} (-\overline{u'_i u'_j}) \quad (14)$$

The turbulence model Transition SST (Shear Stress Transport) is used, which is a combination between the k- ω (used for near-wall situations) and k- ϵ (for far-wall situations) models coupled with two additional transport equations, one for the intermittency and another for the transition onset criteria in terms of momentum-thickness Reynolds number [41]. For the present work, the Transition SST model yields numerical values closer to the experimental values than those resulting from the SST k- ω model, in addition to converging with a smaller number of revolutions, therefore, it is pertinent to use it to conduct the simulations resulting from a large DoE (Design of Experiments), as discussed in section 4.2.

2.3. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

This work considers a Darrieus VAWT operating under inlet velocity (U_∞) of 9 m/s. Since the goal of the present work is to model the rotation movement of VAWT, it is necessary to subdivide the computational domain into three subdomains: a rotating core in which the turbine is located, a stationary domain involving this rotating core, and an additional circular domain around the blades to control the mesh quality around the aerodynamic profile [11]. A sliding interface between the stationary domain and the rotating core allows the turbine to rotate, as shown in Figure 4.

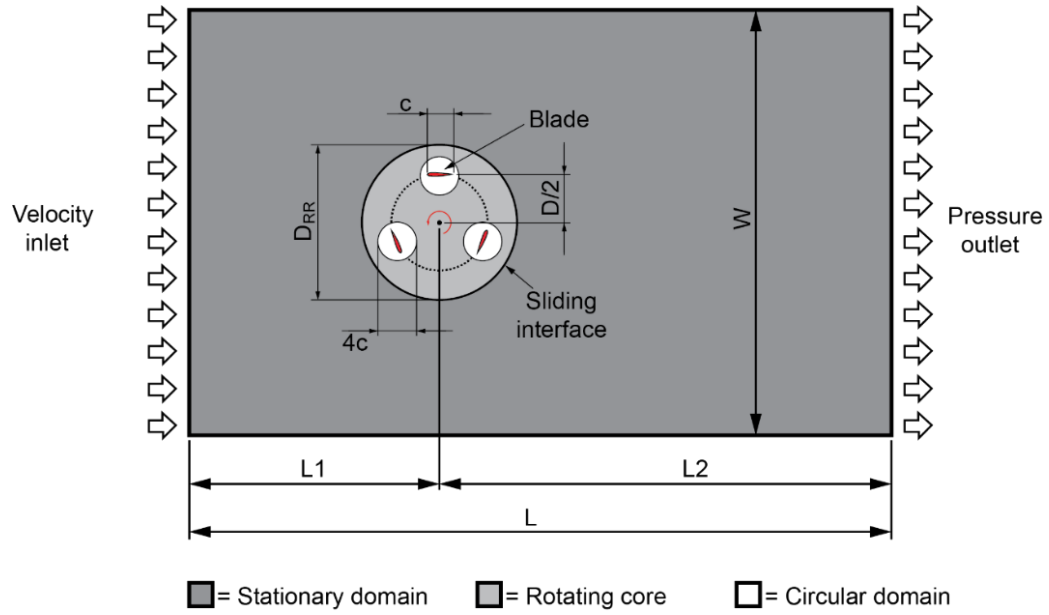


Figure 4. Computational domain and boundary conditions.

The dimensions of the computational domain shown in Figure 4 is in accordance with the recommendations present in the previous works in the literature and are represented in Table 1 [36,41,43].

Table 1. Computational domain dimensions.

Parameter	Value
Inlet Distance (L_1)	10D
Outlet Distance (L_2)	15D
Rotating Domain Diameter (D_{RR})	1,5D
Domain Width (W)	20D

The defined boundary conditions are: constant velocity at the input of the computational domain, fixed pressure (gauge) at the output of the computational domain, symmetry at the top and bottom faces of the domain, non-slip on the blade walls and sliding at the rotating core interface.

Four geometrical characteristics of a small-scale Darrieus VAWT are evaluated. Figure 5 presents a two-dimensional representation of the VAWT, highlighting the parameters: number of blades (N), chord length of the blade (c), turbine diameter (D) and pitch angle (β). Although Figure 5 shows a VAWT with three blades, in the present work VAWTs with two, four and five blades were also investigated.

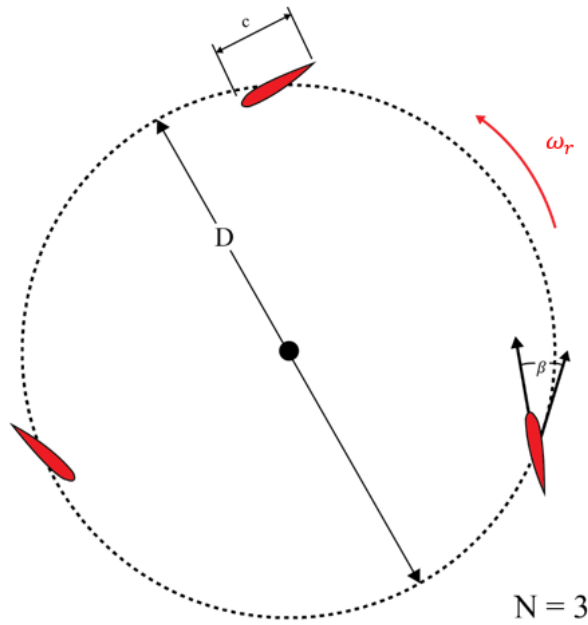


Figure 5. Geometric Parameters of the VAWT.

2.4. MESH AND GRID INDEPENDENCE STUDY

The sliding mesh is a numerical approach used at the interface between rotating and stationary regions to capture the flow behavior due to the rotation of the turbine blades. Therefore, a mesh with unstructured triangular cells was created as shown in Figure 6.

The fine mesh between the stationary region and the rotating core are needed to minimize numerical errors at the interface, as shown in Figure 6a. In addition, the size of the first element on the blade profile (Figure 6b) is taken into account to meet the suggested criteria for the turbulence model ($y^+ < 1$), considering the mesh type of prism layers shown in Figure 6c. The mesh quality criteria are based on orthogonal quality, and the mesh asymmetry (skewness) parameter [44].

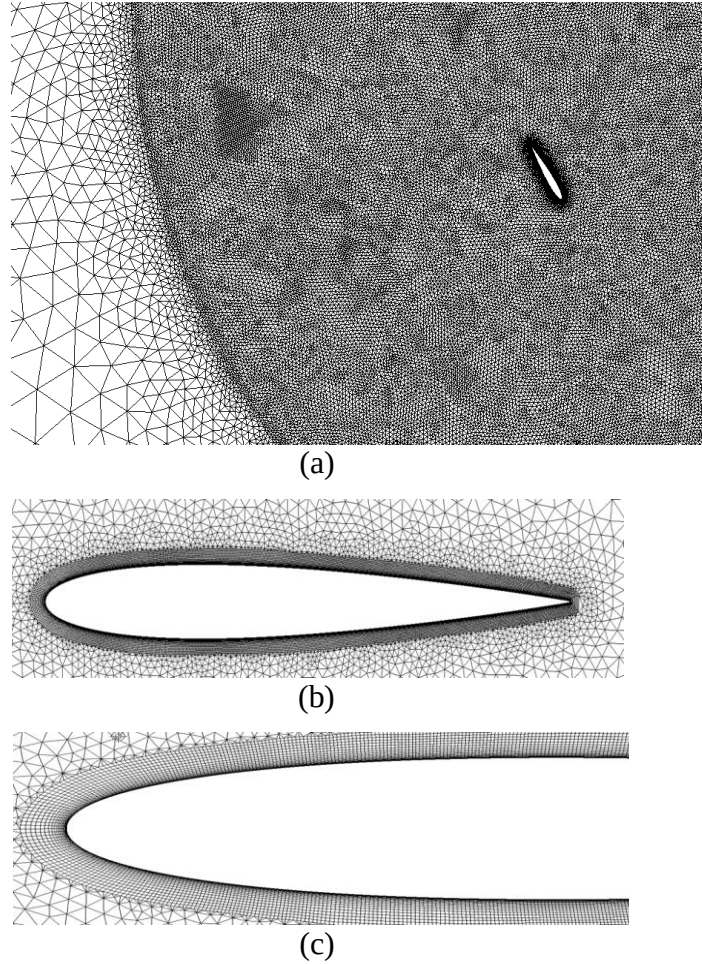


Figure 6. Computational Mesh: (a) Interface between stationary and rotating domains; (b) Details around the Airfoil; (c) Layers of prismatic elements on the NACA0021 Profile.

The mesh density study is performed base on the Grid Convergence Index (GCI) [45] methodology to quantify the discretization errors considering three mesh configurations: coarse, medium and refined. The GCI methodology is based on Richardson's extrapolation method [46,47] and is widely used for CFD analysis [3,22,36,48]. The GCI analysis is performed considering the power coefficient of the VAWT at $\lambda = 2.63$, as shown in Table 2.

Table 2. Main results for the GCI method.

Grid	Coarse (3)	Medium (2)	Fine (1)
Cell Number (n)	165,036	301,755	486,341
Mesh Refinement Factor (s)	-	1.35	1.31
Power Coefficient (C_p)	0.23	0.33	0.33
GCI_{32} (%)	1.55		

According to Table 2, the numerical uncertainty of the modeling on C_p is 1.55%, which is an acceptable value for the purposes of the present work. This percentage reveals that the usage of the medium mesh is suitable since a small variation of C_p is verified in comparison to the fine mesh, which significantly reduces the computational processing time. Thus, the mesh independence was achieved through the GCI methodology.

3. NUMERICAL VALIDATION

The numerical validation is based on the comparison of numerical results and experimental data obtained from measurements in a wind tunnel [11]. The results were also compared with the numerical results published by Hashem & Mohamed [39] and Rezaeiha et al. [43], as presented in Figure 7. Table 3 presents the characteristics of the model used in the numerical validation.

Table 3. Main features of the validation model [11].

Parameter	Description
Aerodynamic Profile	NACA 0021
Number of blades (N)	3
Airfoil chord (c) [mm]	85.8
Turbine Rotor Diameter (D) [mm]	1030
Rotor Height (H) [mm]	1000 (2D simulation)
Mesh/Type	Unstructured/Triangular
Elements	280,638 (Rotating domain) 517,102 (Full Computational Domain)
Solidity (σ)	0.5
Input Velocity (U_∞) [m/s]	9
Azimuthal Angle Step ($\Delta\theta$) [$^\circ$]	0.5
Pitch Angle (β) [$^\circ$]	0
Tip-Speed Ratio (λ)	2.63

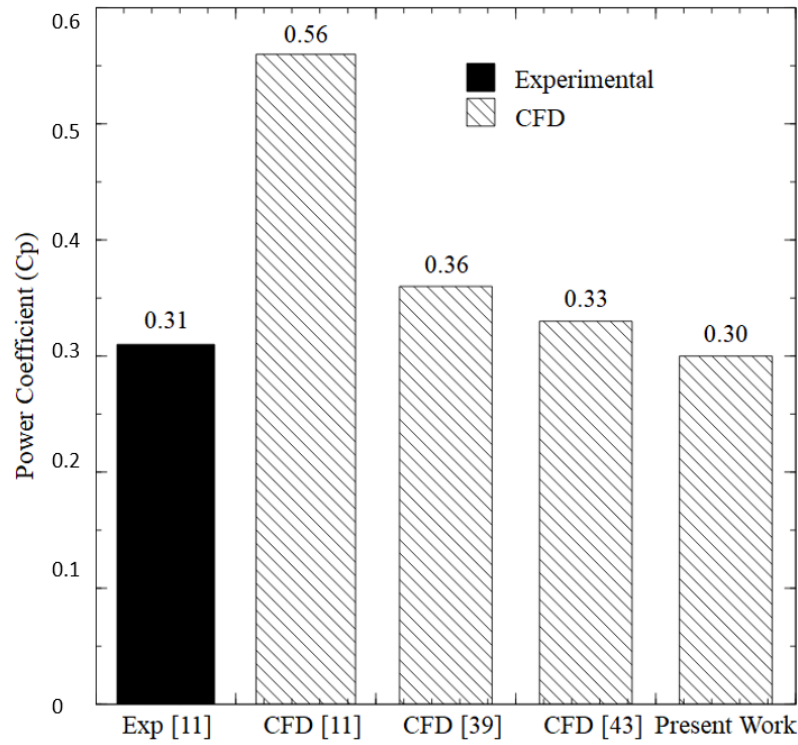


Figure 7. Comparison among experimental data and numerical results.

The comparison of the power coefficient (C_p) shows that the value achieved by the present numerical modeling is in excellent agreement with the experimental data from Castelli et al. [11], showing that the numerical approach and assumptions are robust and adequately reproduce the behavior of a vertical axis wind turbine.

Moreover, the numerical results obtained by Castelli et al. [11] are not sufficiently robust because $\Delta\theta = 1.0^\circ$ was used, which is a high value for the azimuthal angle step, as discussed by Balduzzi et al. [12]. For $\Delta\theta = 1.0^\circ$, the Courant-Friedrichs-Lewy (CFL) criterion is not met, as discussed by Trivellato & Castelli [49]. Regarding the numerical work performed by Hashem & Mohamed [39], although good numerical results are achieved, detailed information about the numerical modeling cannot be verified. Compared to the present work and also to Castelli et al. [11], Hashem & Mohamed [39] used a coarser mesh refinement. In addition, the researchers used the $k-\epsilon$ realizable turbulence model, which was also used by Castelli et al. [11] and other numerical works that failed to characterize the flow behavior through VAWT. The present work used $\Delta\theta = 0.5^\circ$, since the literature indicates that the variation of the azimuthal angle should be as small as possible for a better representation of the physical phenomenon [12]. Although an azimuthal angle of $\Delta\theta = 0.25^\circ$ provides results even closer to the experimental results, the required computational resource would be huge, with prohibitive processing time. Therefore, the choice of $\Delta\theta = 0.5^\circ$ ensures good physical reliability and less

computational effort when running the sensitivity analysis DoE and RSM training set. This same $\Delta\theta = 0.5^\circ$ is also used by Li et al. [50] and studied by Bai et al.[42].

4. SENSITIVITY ANALYSIS USING THE ELEMENTARY EFFECTS (EE) METHOD

4.1. THE EE METHOD

The multiple purposes of SA for engineering designs have turned its usage popular. The basic principle of the many existing SA methods is the evaluation of the change in output variables by modifying the input variables [51,52]. Morris [26] developed a sensitivity analysis classified as ‘one-factor-at-a-time’ method for modifying the inputs and verifying their impact on the output. Its application in computational models with a large number of input parameters or expensive processing time can determine which of them would have important effects on the output parameters [28–30]. This method is known as the elementary effects (EE) method, and it is a simple, but effective way of screening the sample space for important input variables among the many that can be contained in a model. The Elemental Effect is defined by Equation 15.

$$EE_i = \frac{Y(X_1, X_2, \dots, X_i + \Delta, \dots, X_k) - Y(X_1, X_2, \dots, X_k)}{\Delta} \quad (15)$$

where: Δ is the step in the input space sample and $X_i, (i = 1, \dots, k)$ is the independent input variable from 1 to k.

Morris [26] states that r elementary effects have to be considered for each input variable, through a sampling design that constructs r trajectories of $(k + 1)$ points. The total cost of the method is, therefore, the number of trajectories multiplied by the number of independent variables plus one, $r(k + 1)$.

The Morris' original method is able to determine which input variables are important and/or involved in interactions with other variables (non-linear effects). Two sensitivity measures are used for each input variable: the arithmetic mean, μ , of each input EE distribution, which evaluates the importance of the variable, and the normal deviation, τ , of each input EE distribution, which estimates interactions with other factors. These parameters are defined as:

$$\mu_i = \frac{1}{r} \sum_{j=1}^r EE_i^j \quad (16)$$

$$\tau_i = \frac{1}{r-1} \sum_{j=1}^r (EE_i^j - \mu_i)^2 \quad (17)$$

Campolongo et al., [27] proposed a better sensitivity measure, μ^* , which is the average of the EE distribution in absolute values, solving the problem of effects that have opposite signs in non-monotonic models.

$$\mu_i^* = \frac{1}{r} \sum_{j=1}^r |EE_i^j| \quad (18)$$

The classification of non-important input variables requires objective terminology. Vanrolleghem et al. [53] proposed a method for classifying variables as important or unimportant and influential or non-influential. A cut-off threshold is determined by the analyses of Figure 8, which allows the distinction of three different types of variables. The line of $\mu_i^* = 2SEM_i$, is the double of the standard deviation of the EE distribution and is used to determine the effect type of variables [26]. In which $SEM_i = \tau_i r^{-1/2}$, where r is the number of trajectories. Variables that lie below the line $2SEM_i$ and to the right of the threshold have a linear effect on the model outputs. Variables above the $2SEM_i$ line, on the other hand, have a non-linear effect.

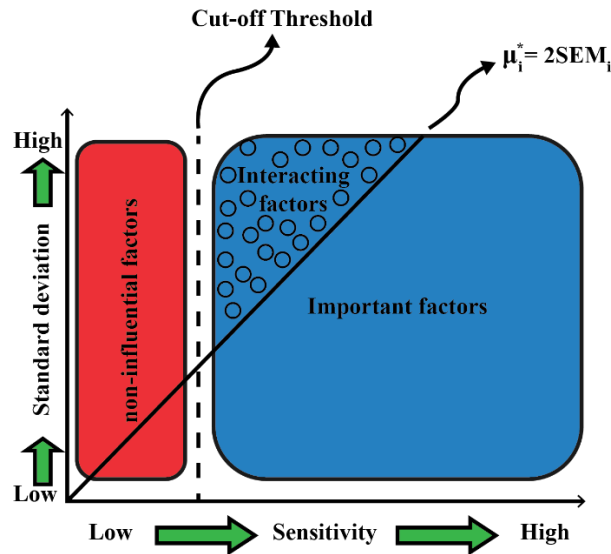


Figure 8. Differentiation of variables of the Morris screening method [53].

To classify the variables as non-influent, a cut-off threshold for the Morris screening method (CT_{Morris}) should be set. Thus, the non-important factors are those that have $\mu_i^* <$

CT_{Morris} . The absolute EE average (μ_i^*) ranking histogram in association with a variable agglomeration of this classification method provides enough insight for the analyst to define an appropriated threshold.

4.2. DESIGN OF EXPERIMENTS (DoE)

The DoE defined to perform the sensitivity analysis of the input parameters of VAWT on the power coefficient (C_p) using Morris method is generated through the Quasi-Optimal Sampling (Quasi-OT) method. Design of Experiments is a branch of applied statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters [54]. Essentially, DoE provides a distribution of input variables in a sample space, then allows statistical tools to be applied to identify main and interaction effects between variables [55].

For the Morris method, the size of the DoE via Quasi-Optimal Sampling depends on the number of variables (k) and trajectories (r) in the sample space $(k+1) \times r$. In the present work, four input variables ($k=4$) and 10 trajectories ($r=10$) were used [56], which results in a total of 50 CFD evaluations. Table 4 shows the lower and upper bands for each input variable range, based on previous work in the literature [14].

Table 4. Input variables bands.

Variable	Lower	Upper
Number of blades (N)	2	5
Airfoil chord (c) [mm]	75.0	95.0
Turbine Rotor Diameter (D) [mm]	950	1150
Pitch Angle (β) [$^\circ$]	-5	5

5. OPTIMIZATION

Despite the increase of computer capacity in recent years, optimization of large models could be prohibited due to the high processing time. To overcome this problem, an approximation of the original model can be done with response surfaces [57], which is achieved by performing only a few original model runs and than training a function that represents accurately the original model. For numerical models with high computational cost, an optimization using response surface has some advantages compared to direct optimization: faster model realization, less computer storage required, easier applicability to sensitivity

analysis methodologies and flexibility to explore different objective functions including the characterization of the Pareto frontier. For high-dimensional models, most effort is spent on developing and calibrating a response surface (RS). As proposed by Salviano et al. [29], the same DoE used for sensitivity analysis by Morris method is also applied to RS training. Moreover, the RS testing was evaluated by five additional numerical simulations (10% of the total number of cases) generated through ULHS [35]. Five methods of RS were evaluated: Stepwise Regression [58], Gaussian Process [59], Kriging [59], Radial Basis Function [60] and Smooth Spline ANOVA [61], all methods already implemented into the software ModeFRONTIER. Table 5 shows the quality criteria for each RS evaluated.

Table 5. Quality criteria of the response surface trained for Power Coefficient (Cp)

RS Method	R²	Max. Abs. Error (%)	Max. Rel. Error (%)
Stepwise Regression [58]	0.983	1.6	11.5
Gaussian Process [59]	0.916	3.1	17.0
Kriging [59]	0.856	3.7	26.4
Radial Basis Function [60]	0.846	3.8	10.6
Smooth Spline ANOVA [61]	0.800	5.0	18.8

After RS training and testing, Stepwise Regression method [58] was chosen for optimization analysis in the present work, since the square regression (R^2) is the closest to the unit, besides the average and maximum percentual error have lower values than another RS methods.

5.1. OPTIMIZATION STATEMENT

An unconstrained optimization procedure is performed using the improved version of the Non-dominated Sorting Genetic Algorithm (NSGA-II) already implemented in ModeFRONTIER, which is a computationally fast and elitist evolutionary algorithm that can maintain a good spread and convergence of solutions [62]. The optimization statement is:

$$\text{Find } X = \begin{Bmatrix} N \\ c \\ D \\ \beta \end{Bmatrix} \text{ that maximizes the Power Coefficient, } Cp(X)$$

6. RESULTS AND DISCUSSION

This section presents results for the sensitivity analysis, optimization and dynamic flow phenomenology. In the sensitivity analysis, the Morris method was used to rank the influence of the geometric input parameters of the vertical-axis wind turbine. Afterward, the results of a single-objective unconstrained optimization are presented, together with a detailed discussion on the differences between the base and optimized configurations. Finally, the impact of pitch angle (β) and solidity (σ) on power coefficient (C_p) is investigated.

6.1. MORRIS SENSITIVITY ANALYSIS

Morris method analysis was performed, aiming to show the degree of importance of the input variables on the output and also look for interaction effects. In this sense, to evaluate the performance of a Darrieus VAWT, four geometric parameters were considered as input variables (Table 4): number of blades (N), airfoil chord length (c), turbine rotor diameter (D), and pitch angle (β). The output of interest is the power coefficient (C_p) of the wind turbine.

Figure 9 shows the main effects for each input variable considering the output of interest. In addition, it shows a cumulative effect curve with points between the histogram bars. As shown in Figure 9a, the pitch angle (β) is the most important parameter on the wind turbine performance. The chord length (c), number of blades (N), and rotor diameter (D) have much less influence on the power coefficient (C_p), although the sum of these contributions (c , N and D) have a significant influence on the power coefficient of the wind turbine. Therefore, no input variable should be excluded from optimization procedures, since all of them have a certain degree of importance. Figure 9b shows that the input variables are below the 2SEMi reference line, which means that their main effects are much larger than their interaction effects. In other words, the interaction effects can be considered insignificant. The cut-off threshold for the Morris screening (CT_{Morris}) method was defined as the value of μ^* that takes into account more than 80% of the variations of the output. Therefore, the input parameter D in the left side of the threshold could be considered non-significant. However, it is very close to this reference line and its effect on power coefficient could be considered still significant if compared to chord (c) and number of blades (N). Thus, all input variables are maintained for the optimization.

As presented in Section 4.1, the number of trajectories (r) is a critical parameter to ensure the robustness of the Morris method [26]. Too many trajectories would increase

computational efforts and not enough trajectories would result in misleading sensitivity measures. In this sense, to ensure the robustness of the work, the Response Surface (RS) trained by the "Stepwise Regression" method was used to evaluate the consistency of the screening analysis. By this approach, it is possible to analyze the extrapolation of the number of trajectories for the Morris method, using $r = 10, 20, 40, 80, 160$ and 320 . Figure 10 shows the impact of the number of trajectories on the sensitivity measures of each input variable on the output variable (C_p), starting with the original DoE containing ten trajectories evaluated by the CFD model up to the trajectories evaluated by the RS models.

As presented by Figure 10, the variables of less influence (N , c , and D), maintain a low influence for all numbers of trajectories investigated. Regarding the diameter (D), it behaved as the least influential variable for all the numbers of trajectories used. In relation to the variables number of blades (N) and chord length (c), for the CFD model ($r=10$), these had influences with very close values; when increasing the number of trajectories, the ranking between them changed, however always being with very close values. Finally, when observing the behavior of the pitch angle variable (β), it is noted that its effect remains for all cases as the most influent on the variable of interest (C_p). Overall, conclusions which are shown in Figure 9 for 10 trajectories ($r=10$) are robust and reliable since the extrapolation analysis showed that for all input parameters the trend of the sensitivity measures is slightly changed with the increase of the number of trajectories.

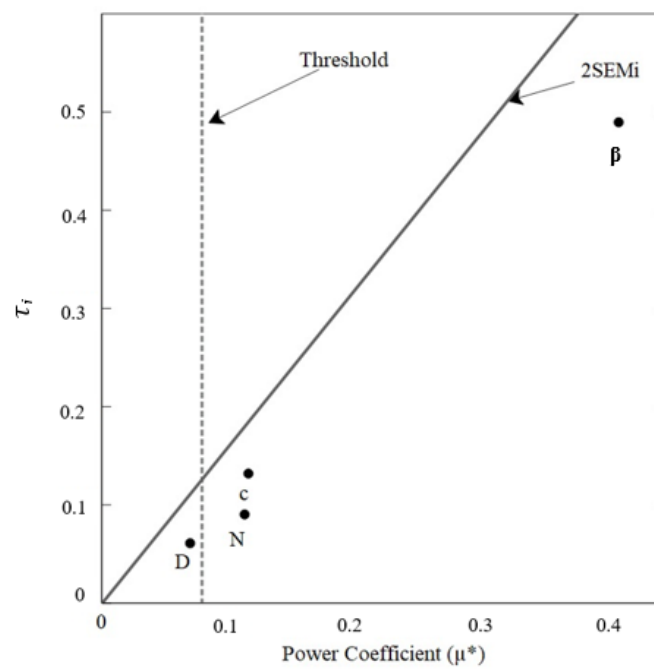
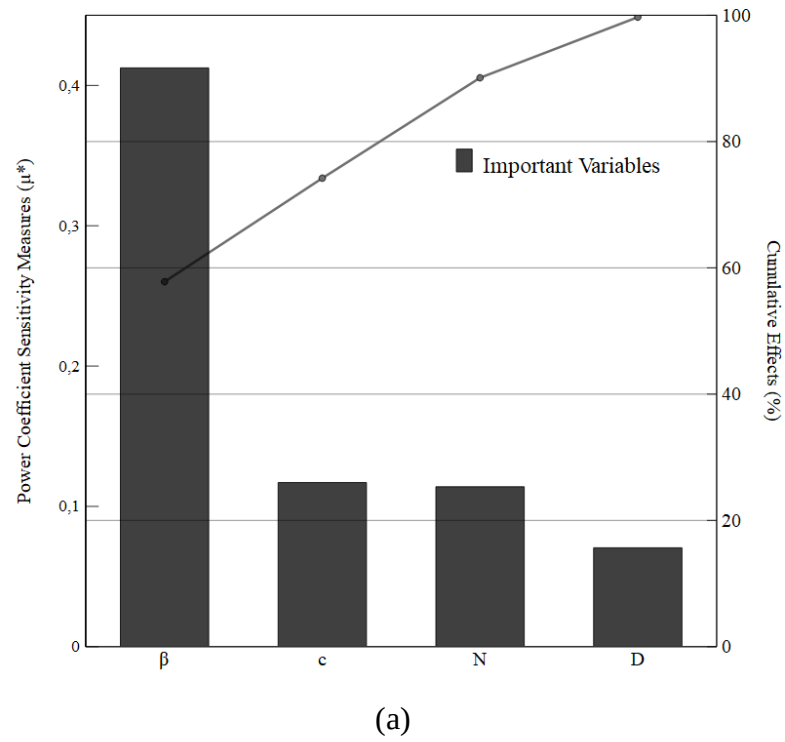


Figure 9. Sensitivity measure of the effects from Morris method analysis on the Power Coefficient (C_p): (a) Histogram bars showing the input variables effects; (b) Interaction effects analysis by via the Morris method.

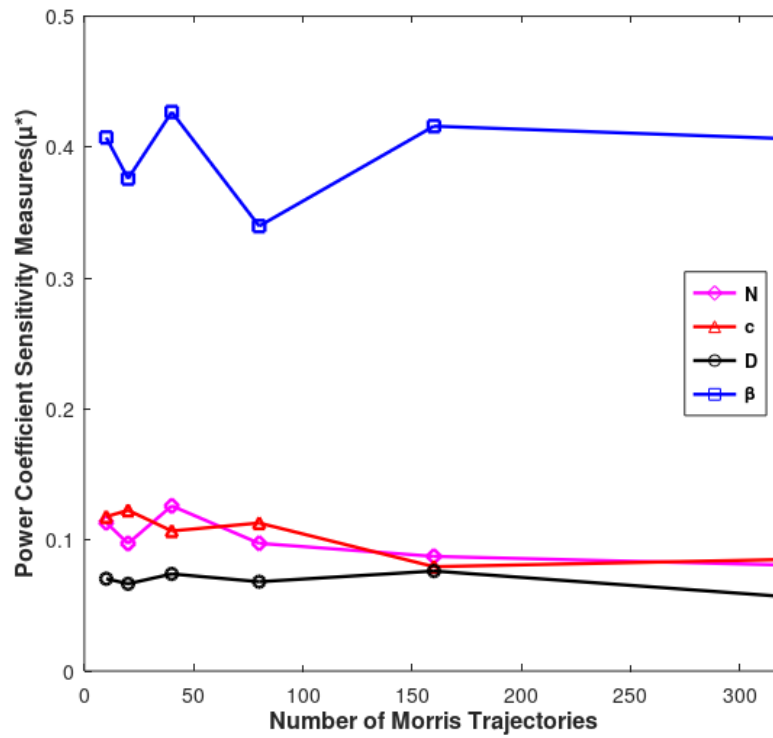


Figure 10. Analysis of the Influence of Extrapolation of the number of trajectories of the Morris method on the variable of interest (C_p).

6.2. OPTIMIZATION

An unconstrained optimization procedure is performed through Stepwise Regression RS and NSGAII algorithm, as discussed in section 5. Table 6 shows the optimal configuration found by the optimization procedure compared to the base configuration according to Castelli et al. [11]. The result of the power coefficient from RS is checked by the CFD analysis.

Table 6. Comparison of the input and output variables for the base and optimal configurations.

Case	Model	N	c [mm]	D [mm]	β [°]	C_p
Base configuration	CFD	3	85.8	1030.0	0.0	0.30
Optimization	RS	3	91.0	965.0	-3.3	0.41
	CFD	3	91.0	965.0	-3.3	0.42

The optimal configuration found by RS methodology agrees with the CFD analysis since no significant difference for the power coefficient (C_p) is observed. This shows that the RS trained using the same DoE for Morris method (Quasi-OT sampling) is robust, considering

a different application than those conducted by Salviano et al. [29]. The power coefficient (C_p) for the optimal configuration increased by 40% compared to the base configuration.

As shown by Table 6, the base configuration presents the same number of blades as the optimized configuration ($N=3$), which is similar to several small-scale wind turbines available for commercialization. However, the chord (c) and diameter (D) values are different, which provides solidity values of 0.50 and 0.57 for the base and optimized configurations, respectively. Regarding the pitch angle (β), the optimized configuration presents a -3.3° angle, which increased the efficiency of the VAWT.

Figure 11 presents a comparison of the instantaneous torque coefficient (C_t) for the optimized and base configuration, showing that the values of the instantaneous torque coefficient (C_t) of the optimized VAWT does not assume negative values at their minimum points, whereas for the base VAWT some negative values can be observed.

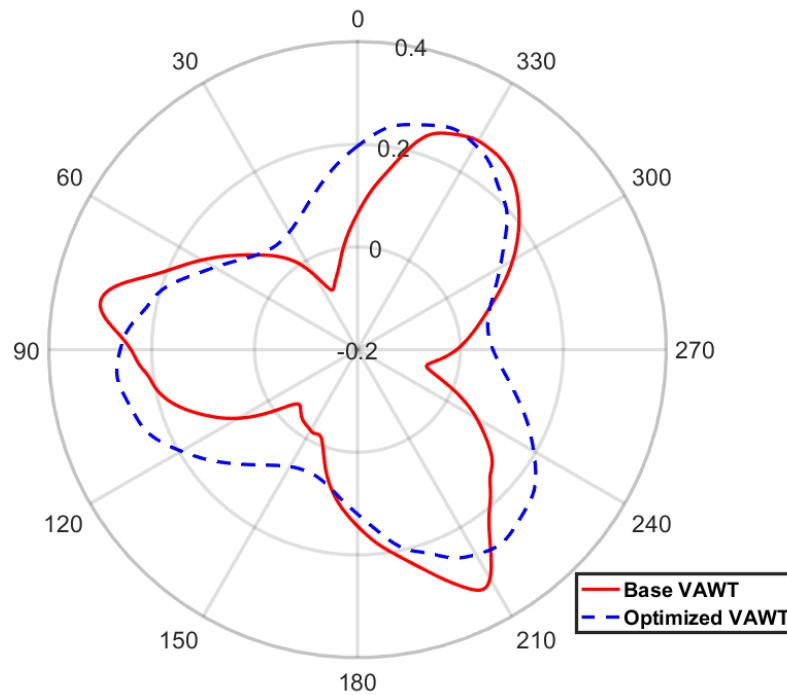
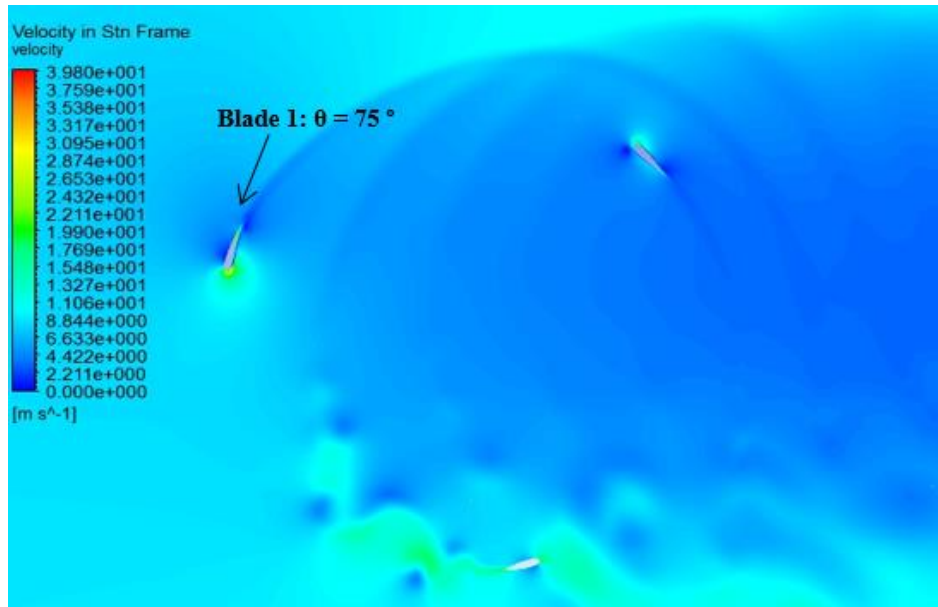


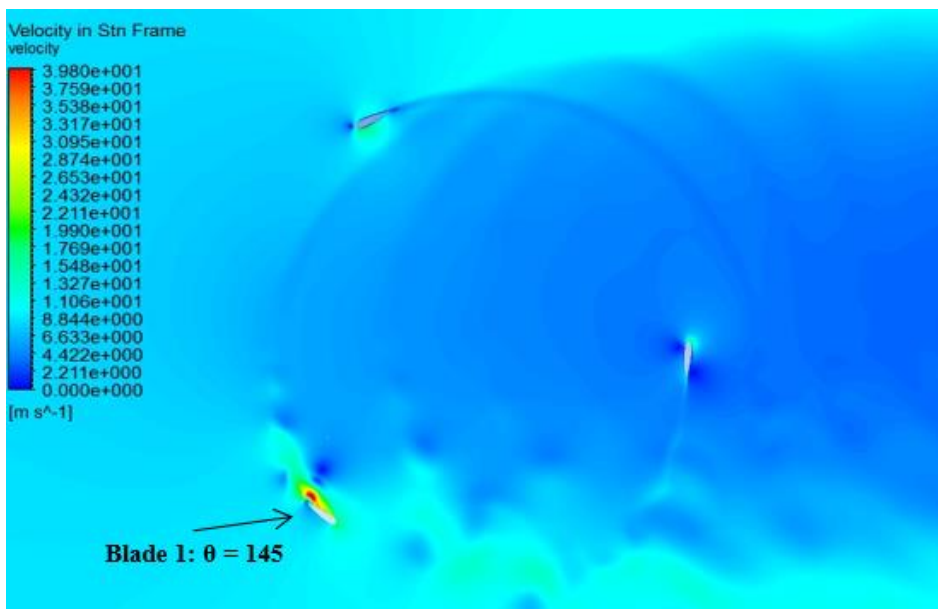
Figure 11. Comparison of the instantaneous torque coefficient (C_t) between the base and optimized VAWT configurations.

This result justifies the increase of 40% in the power coefficient (C_p) of optimized VAWT compared to base VAWT, according to the values in Table 6. Figure 11 also shows that $\theta = 75^\circ$ is a point of maximum C_t and $\theta = 145^\circ$ is a point of minimum C_t for the base VAWT configuration. Moreover, $\theta = 95^\circ$ is a point of maximum C_t and $\theta = 155^\circ$ is a point of minimum

C_t for the optimized VAWT configuration. Thus, Figure 12a and Figure 12b present the velocity fields at these points for the base and optimized VAWT configuration, respectively. It is worth mentioning that regarding the azimuthal angle (θ), it was adopted that the rotation happens counterclockwise and that the turbine starts from $\theta=0^\circ$ with blade 1 at the horizontal direction.

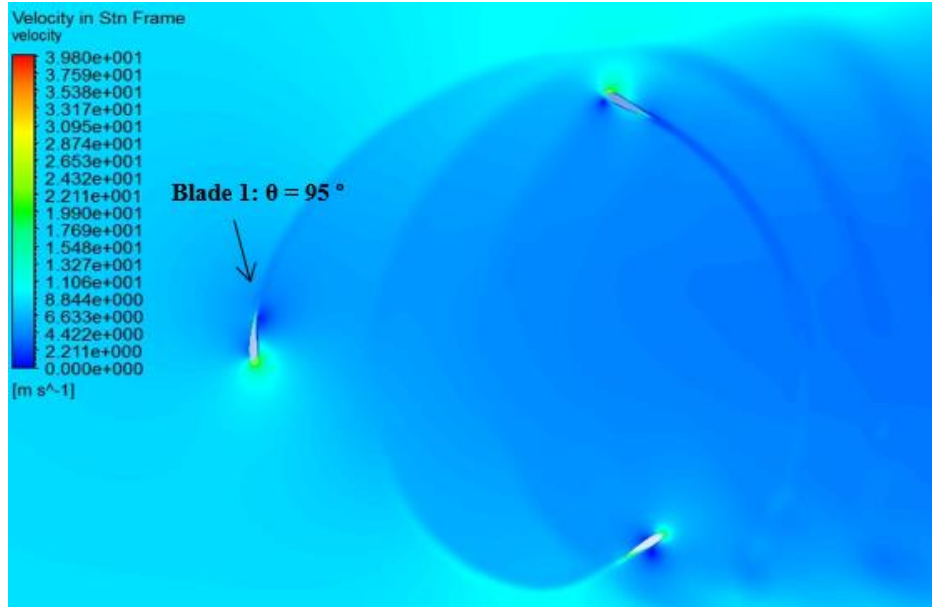


(a)

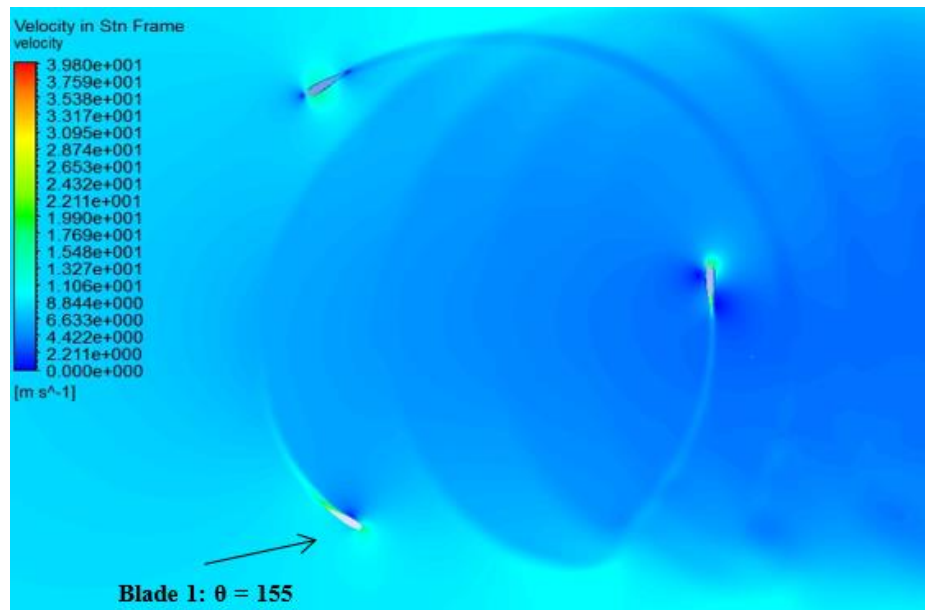


(b)

Figure 12. Velocity field for the base VAWT configuration: (a) At maximum C_t , $\theta = 75^\circ$; (b) At minimum C_t , $\theta = 145^\circ$.



(a)



(b)

Figure 13. Velocity field for the optimized VAWT configuration: (a) At maximum C_t , $\theta = 95^\circ$; (b) At minimum C_t , $\theta = 155^\circ$.

Figure 12b shows drag zones at the azimuthal position $\theta = 145^\circ$ for the base VAWT configuration indicating flow separation and the formation of wake region which corroborates the result presented by Figure 11 where the negative value of C_t at this position is observed. This unwanted dynamic flow phenomenology is not observed for optimized VAWT, Figure 13b, also corroborates to results shown in Figure 11. In general, the flow-through the optimized VAWT is much more smooth than the one observed though the base VAWT, which can be

seen in detail in Figure 14 and Figure 15. In these figures, the pressure field is shown and details of the flow at the maximum and minimum C_t points, respectively, can be analyzed for the base and optimized VAWT configurations.

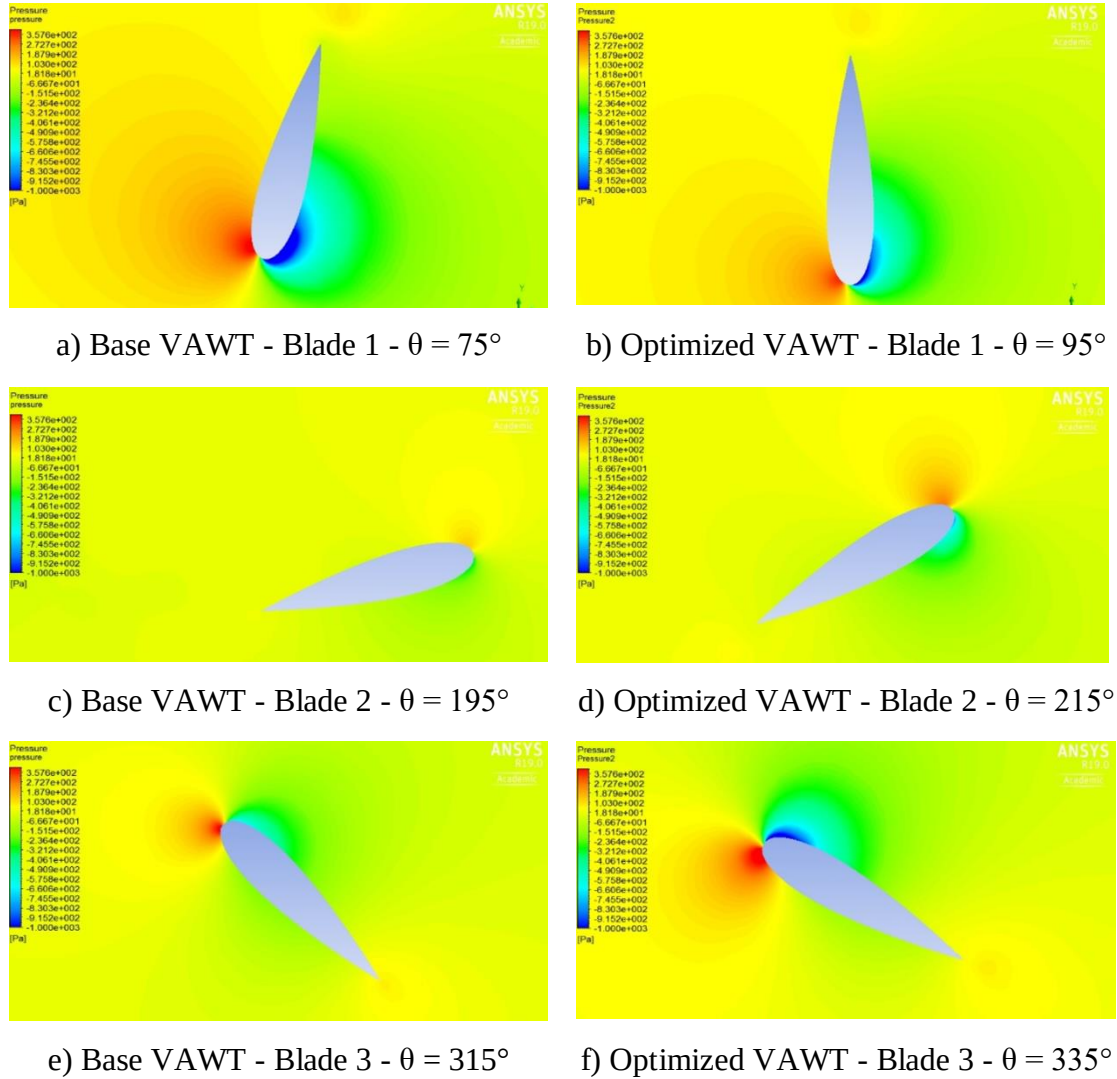


Figure 14. Pressure field around the blades for the base and optimized VAWT configurations at the maximum C_t values.

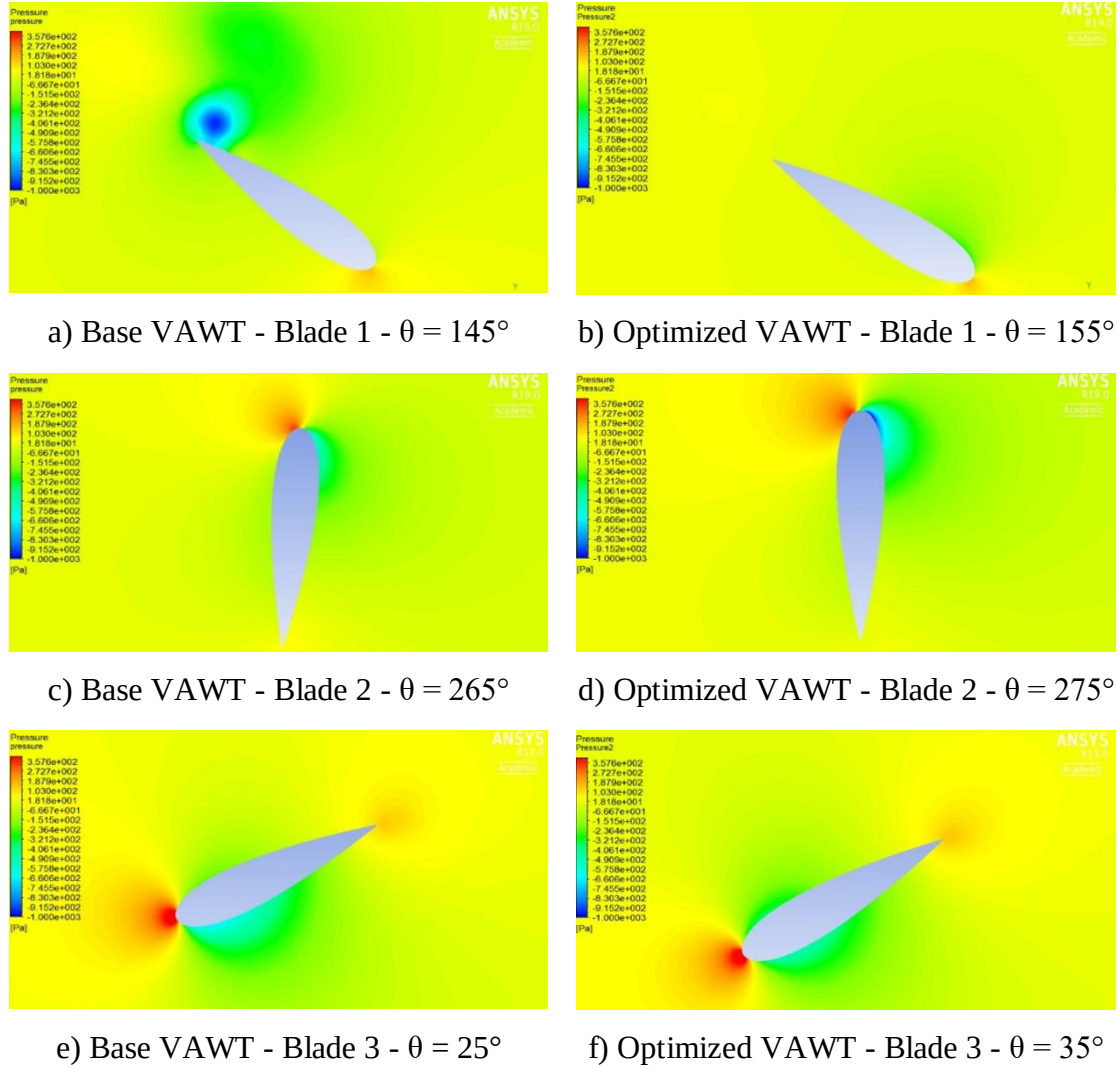


Figure 15. Pressure field around the blades for the base and optimized VAWT configurations at the minimum C_t values.

Figure 14a-b show the high influence of blade 1 to reach higher torque, which is due to the pressure difference of the lower and upper side from stagnation point, promoting a high lift force and, consequently a higher torque coefficient (C_t).

At the position related to the minimum torque coefficient (C_t), the dynamic flow is smoother for the optimized VAWT than the base VAWT configuration. Figure 15a shows a region of low pressure at the trailing edge of the blade due to separation of the flow, causing loss of the lift and, consequently, decreasing the torque coefficient of the VAWT. On the other hand, Figure 15b shows that the unwanted flow dynamics shown in base VAWT is not observed for optimized VAWT, which contributes to increasing the energy conversion of the wind turbine.

6.3. ANALYSIS OF THE PITCH ANGLE (β)

According to Figure 9, the pitch angle (β) is the most important input parameter among those studied herein towards the power coefficient (C_p) of the wind turbine. The strategy for the present analysis is to fix the pitch angle (β) and submit the other variables to the optimization procedure, obtaining the maximum C_p due to optimal chord (c), number of blades and diameter (D) for each pitch angle, which are shown in Table 7.

Table 7. Comparative analysis between CFD and RS of C_p values for β operating range from -5° to 5° .

β [$^\circ$]	N	c [mm]	D [mm]	C_{p_RS}	C_{p_CFD}	σ
-5.0	3	93.0	970.0	0.40	0.42	0.57
-4.0	3	92.0	965.0	0.41	0.42	0.57
-3.3	3	91.0	965.0	0.41	0.42	0.56
-2.0	3	88.0	960.0	0.40	0.40	0.55
-1.0	3	87.0	960.0	0.37	0.37	0.54
0.0	3	86.0	960.0	0.32	0.32	0.54
1.0	3	86.0	965.0	0.26	0.24	0.53
2.0	3	88.0	1150.0	0.19	0.17	0.46
3.0	3	88.0	1150.0	0.13	0.13	0.46
4.0	3	89.0	1150.0	0.06	0.03	0.46
5.0	3	90.0	1150.0	-0.01	-0.02	0.47

The approach presented in Table 7 shows that the response surface (RS) is robust, especially close to the points of the highest power coefficient (C_p). Thus, it is verified that as the pitch angle decreases, the C_p increases until a maximum value is reached between pitch angles of -3° and -4° , as presented previously in Table 6.

Figure 16 shows the aerodynamic impact on the turbine power coefficient (C_p) through analysis of the averages of lift coefficient (C_l), drag coefficient (C_d) and its polar coefficient (C_l/C_d) for each pitch angle (β).

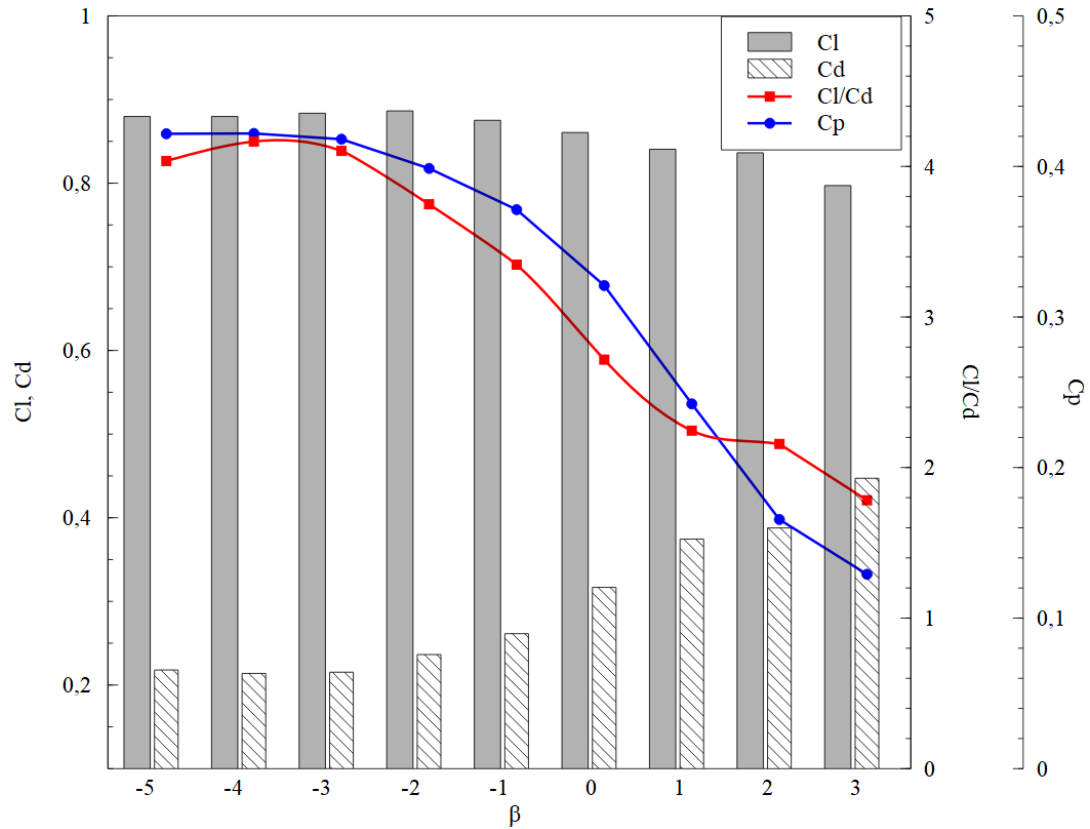
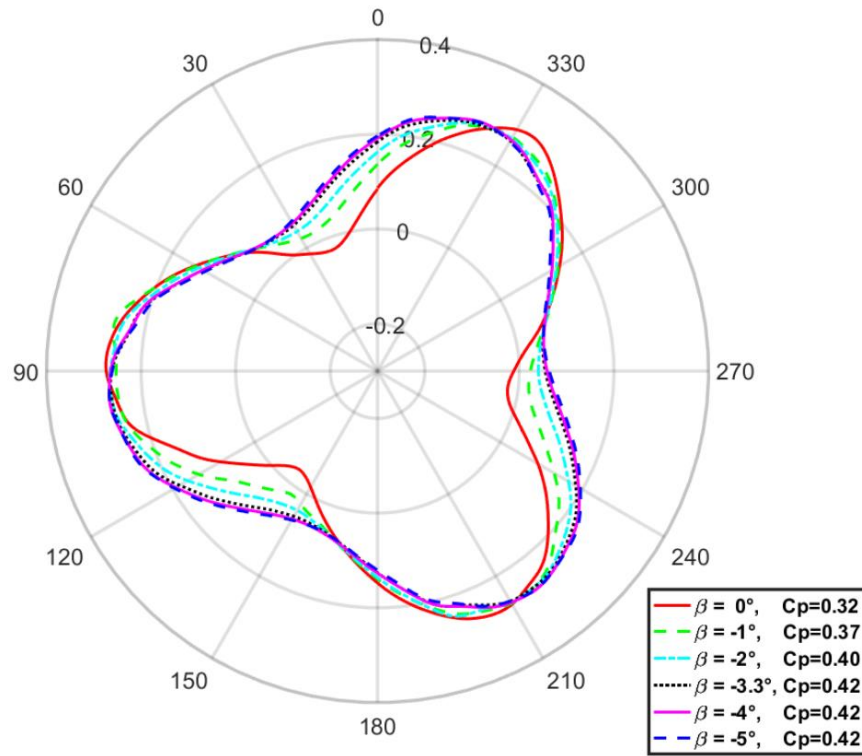
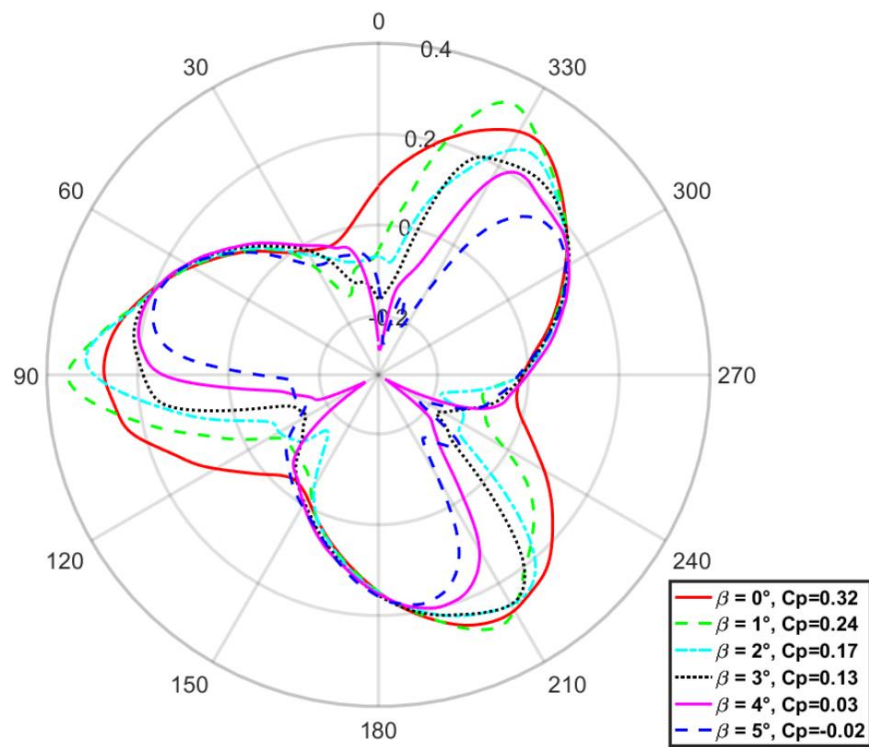


Figure 16. Comparison between Cl , Cd and C_p by varying the pitch angle (β)

The increase of the average lift coefficient (Cl) should be combined with a low average drag coefficient (Cd), resulting in a high average aerodynamic efficiency (Cl/Cd), which increases the average power coefficient (C_p). This scenario is observed for $\beta = -5^\circ, -4^\circ$ and -3° . This becomes more evident when analyzing the columns for $\beta = -2^\circ$, in which although Cl kept similar values of those for $\beta = -5^\circ, -4^\circ$ and -3° , Cd has increased, which decreases the ratio Cl/Cd and, consequently, reduces the power coefficient (C_p). Figure 17 presents the influence of the pitch angle (β) on the instantaneous torque coefficient (C_t) of the wind turbine related to VAWT configurations shown in Table 7.



(a)

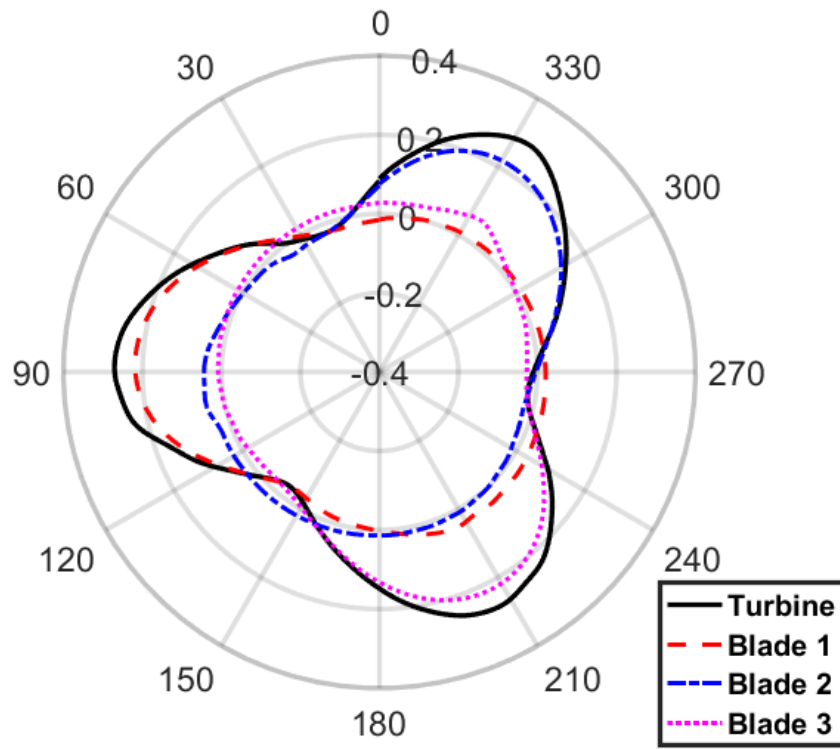


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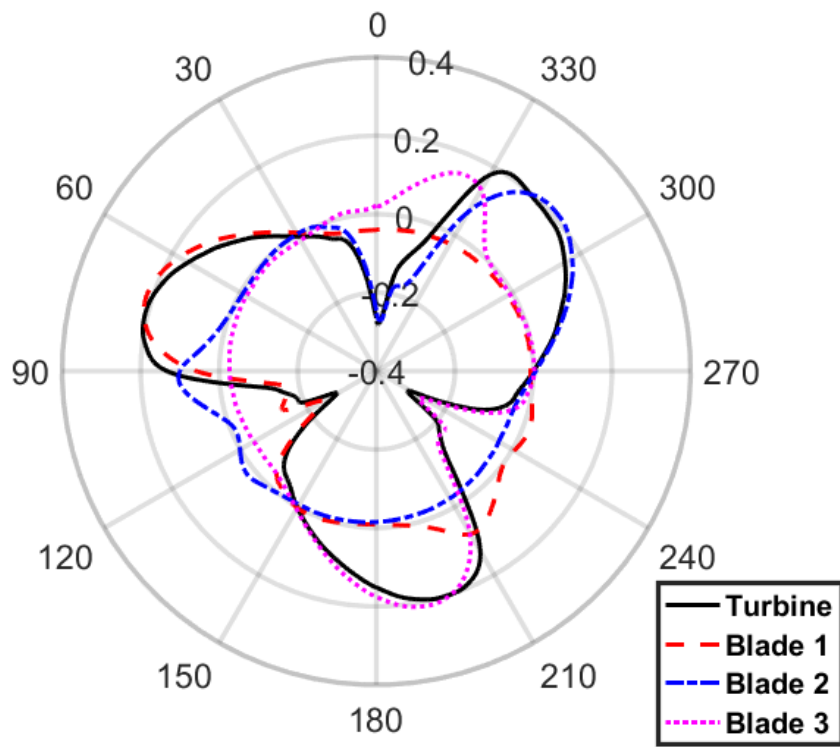
Figure 17. Influence of the pitch angle (β) on the torque coefficient (C_t) of the wind turbine for (a) negative angles and (b) positive angles.

Figure 17a shows that for a symmetrical profile, negative pitch angles up to $\beta = -3.3^\circ$ provide an increase in wind turbine efficiency. On the other hand, as it tends to positive values (Figure 17b), the energy conversion decreases. Figure 17a also shows that as one decreases the pitch angle, the points of minimum C_t get smoothed and, consequently, become less influential on the loss of efficiency. In this way, the flow dynamics for the optimal configuration ($\beta = -3.3^\circ$) and the base configuration ($\beta = 0^\circ$) has been discussed in detail in section 6.2. However, the study of flow dynamics focusing on positive pitch angles is also important, since the behavior of the flow that decreases the energy conversion of VAWT could be avoided in wind turbine design. Thus, Figure 18 presents the average Torque Coefficient (C_t) considering its behavior for each blade for the cases with $\beta = 0^\circ$ and $\beta = 4^\circ$, respectively, according to VAWT configurations shown in Table 7.

Figure 18 shows that a single blade, at a given region, mostly influences the average torque coefficient (C_t). In Figure 18a, for example, it can be seen that blade 1 has a strong influence on the performance of the wind turbine between $\theta = 30^\circ$ and $\theta = 150^\circ$, i.e., each blade has a strong influence on one-third of the revolution of the wind turbine. Moreover, one can highlight in Figure 18b a higher influence of blade 1 on the average C_t between $\theta = 15^\circ$ and $\theta = 120^\circ$. Figure 18b also shows that between $\theta = 85^\circ$ and $\theta = 125^\circ$, the VAWT configuration with $\beta = 4^\circ$ presents a sharp drop in the average C_t , caused by phenomena involved in blade 1. Thus, Figure 19 presents the comparison of the pressure fields for the cases with $\beta = 0^\circ$ and $\beta = 4^\circ$ for blade 1 between $\theta = 85^\circ$ and $\theta = 125^\circ$ for VAWT configurations with the same solidity value.

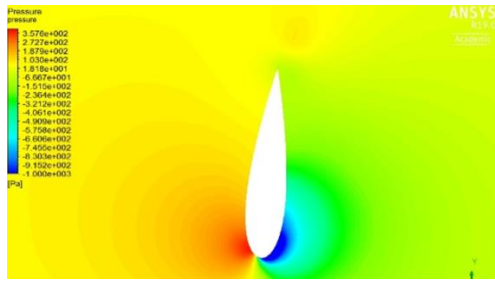
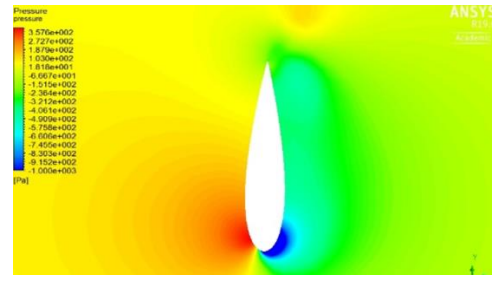
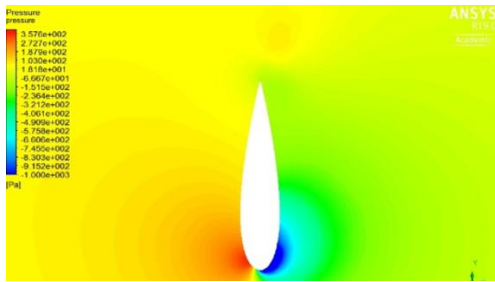
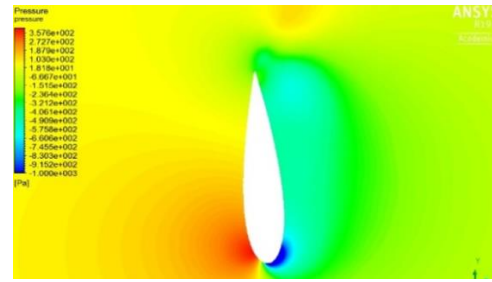
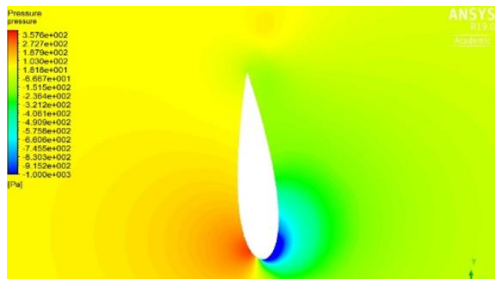
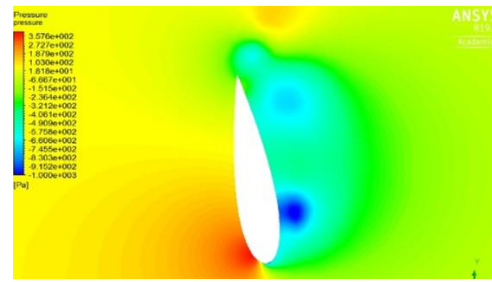
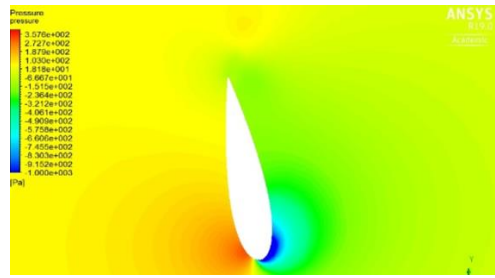
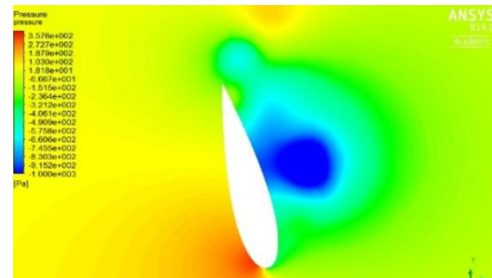
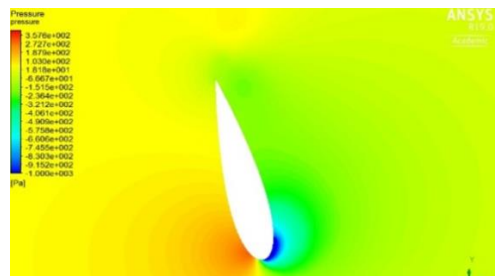
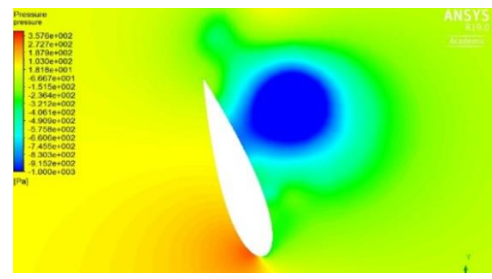


(a)



(b)

Figure 18. Average torque coefficient (C_t) for turbine and for each blade for different pitch angle (a) $\beta = 0^\circ$ and (b) $\beta = 4^\circ$.

a) $\beta = 0^\circ - \theta = 85^\circ$ b) $\beta = 4^\circ - \theta = 85^\circ$ c) $\beta = 0^\circ - \theta = 90^\circ$ d) $\beta = 4^\circ - \theta = 90^\circ$ e) $\beta = 0^\circ - \theta = 95^\circ$ f) $\beta = 4^\circ - \theta = 95^\circ$ g) $\beta = 0^\circ - \theta = 100^\circ$ h) $\beta = 4^\circ - \theta = 100^\circ$ i) $\beta = 0^\circ - \theta = 105^\circ$ j) $\beta = 4^\circ - \theta = 105^\circ$

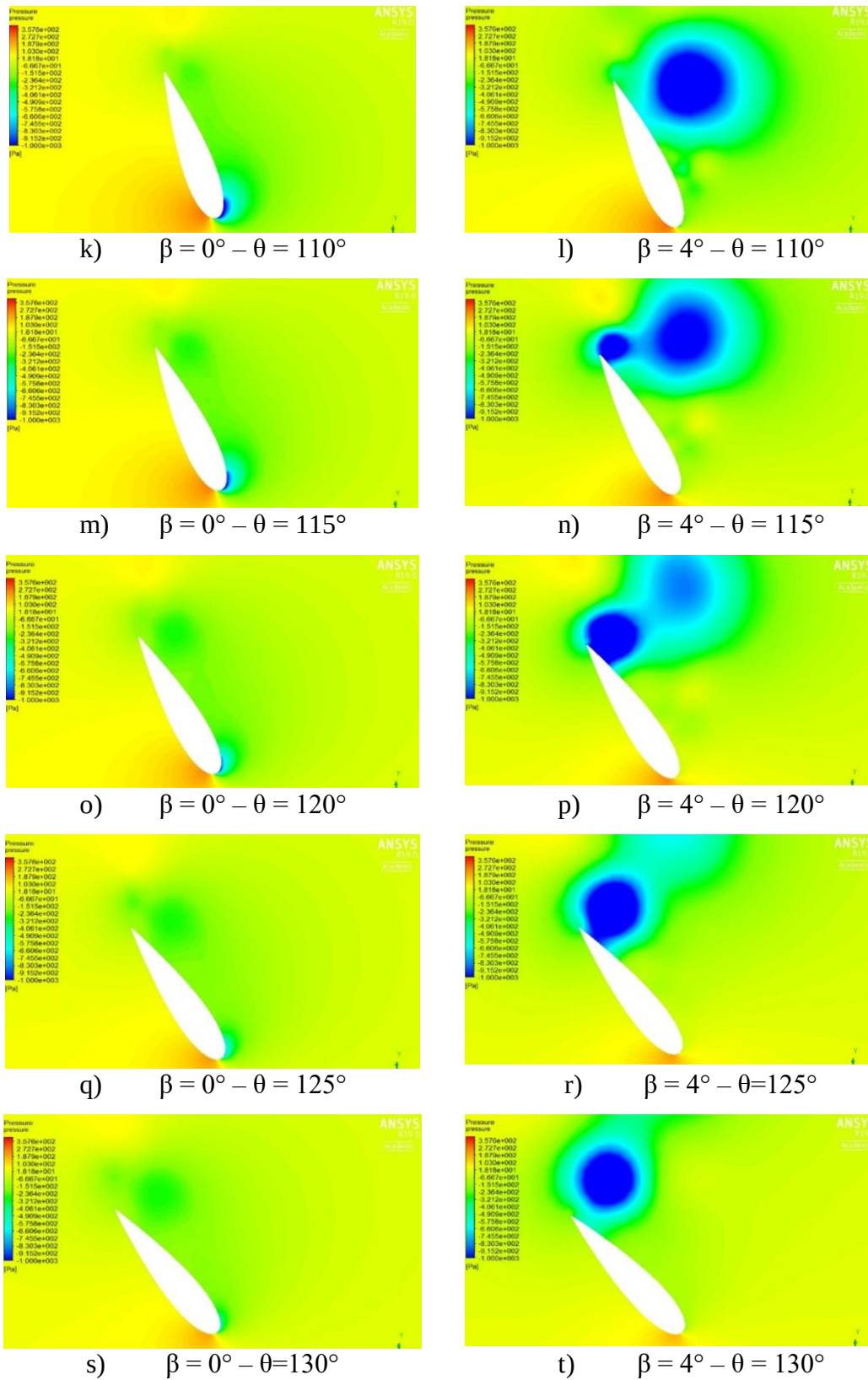


Figure 19. Comparison of pressure fields between VAWT configuration with $\beta = 0^\circ$ and $\beta = 4^\circ$ for the blade 1.

Figure 19 shows that for $\beta = 0^\circ$ a high lift-force occurs on the blade between $\theta = 85^\circ$ and $\theta = 95^\circ$, which is due to the high-pressure difference at the leading edge of the profile (Figure 19a, c and e). This behavior is critical to reaching a high torque coefficient (C_t), as can be observed in Figure 18a. Concerning to the configuration with $\beta = 4^\circ$, it is noted that although at $\theta = 85^\circ$ (Figure 19b) the pressure difference at the leading edge is significant, low-pressure zones are observed throughout the blade at the lower surface. At $\theta = 95^\circ$ (Figure 19f) there is a first vortex shedding on the blade at the lower surface near the leading edge of the profile. This vortex has a high influence on flow dynamic at $\theta = 100^\circ$ and $\theta = 105^\circ$ (Figure 19h and j), until flow detachment occurs at $\theta = 110^\circ$ (Figure 19l). Evaluating Figure 18b, it is observed that the torque coefficient (C_t) due to blade 1 tends to increase again after the detachment of this vortex. However, this first vortex contributes to generate a second vortex on the blade trailing edge, as shown at $\theta = 115^\circ$ (Figure 19n) and $\theta = 125^\circ$ (Figure 19r).

Overall, for a symmetrical profile, the increase of the pitch angle increases the probability of separation of the flow, reducing the lift force and, consequently, decreasing the aerodynamic efficiency.

6.4. ANALYSIS OF SOLIDITY (σ)

The screening analysis from Morris method considering the input variables N , c and D , showed a significant influence on the power coefficient (C_p) of the VAWT. Therefore, a detailed analysis is performed considering the solidity (σ), according to Equation (12). Figure 20 presents the influence of solidity on the power coefficient (C_p) of the wind turbine for $\beta = -5^\circ$ obtained from the DoE configurations used for the screening analysis by Morris method.

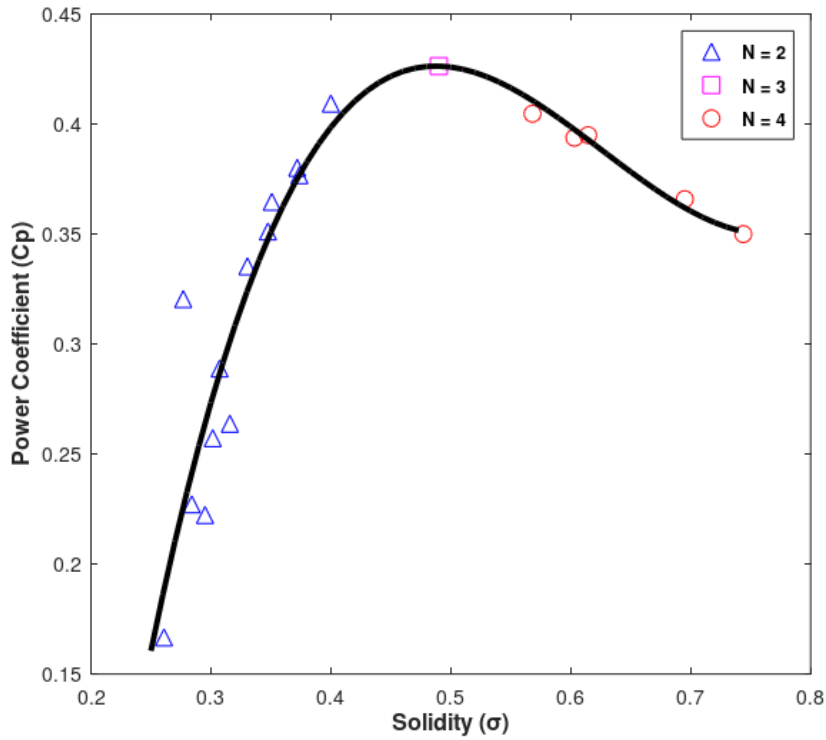
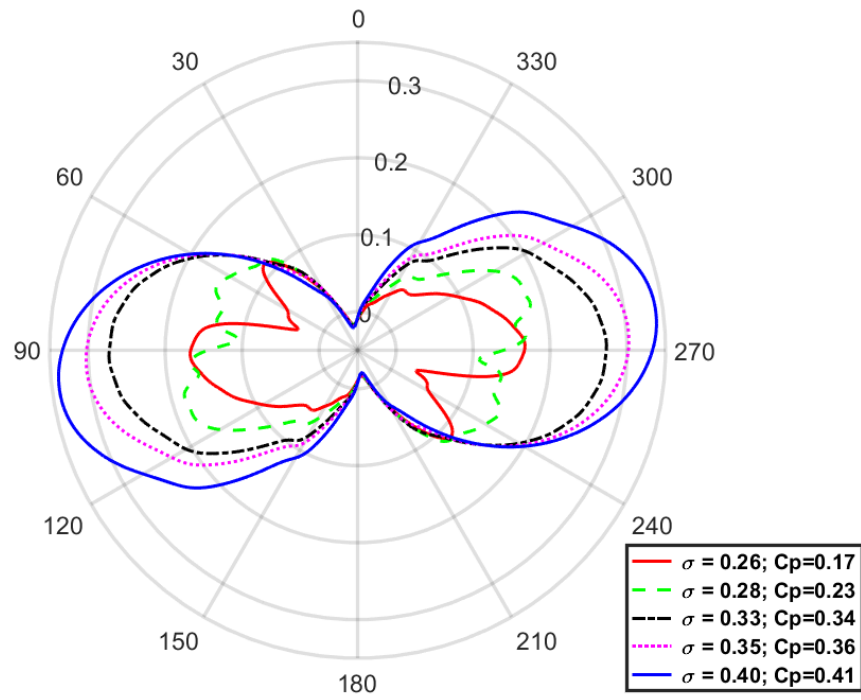


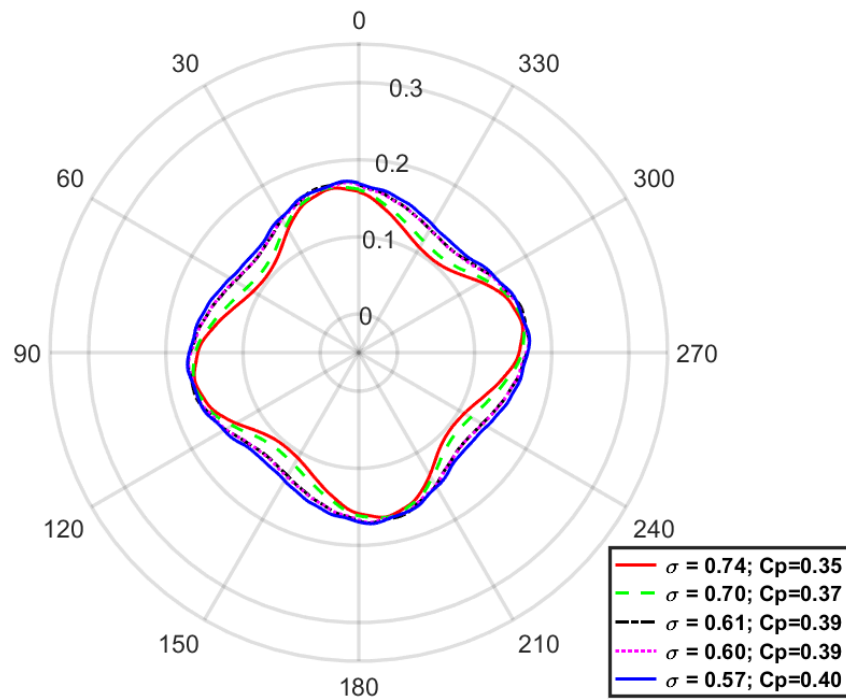
Figure 20. Influence of Solidity (σ) on the power coefficient (C_p) of the wind turbine for $\beta = -5^\circ$.

Sabaeifard et al. [15] report that solidity values in the range of 0.3-0.5 yield better turbine performance. The work of Sungjun et al. [63] indicates for $\lambda=2.63$ a maximum C_p at $\sigma = 0.5$. Furthermore, Sungjun et al. [63] show that for solidity value of $\sigma = 0.2$ a significant drop in turbine performance occurs at the same λ . On the other hand, according to Sungjun et al. [63], solidity values $\sigma = 0.7$ are effective for low λ , reaching a maximum C_p at $\lambda = 2.4$. However, those works have not considered in their analysis the application of optimization methods to find optimal VAWT configuration considering the input variables β , N , c and D . Furthermore, at $\lambda = 2.63$ the present work found a suitable VAWT configuration within the solidity range of 0.4-0.6, according to Figure 20. A maximum power coefficient (C_p) is found for $\sigma = 0.5$, corroborating the analyses of Sabaeifard et al. [15] and Sungjun et al. [63].

Figure 20 also shows that high values of C_p can be reached for two blades ($\sigma = 0.40$) and four blades ($\sigma = 0.57$). Moreover, related to manufacturing process to build a wind turbine with two blades is cheaper than a VAWT with four blades. However, turbines with two blades have been reported to present problems related to self-start (low torque), as addressed by Sungjun et al [35], and also structural issues concerning fatigue. To further detail the influence of solidity on the wind turbine performance, Figure 21 presents the instantaneous torque coefficient (C_t) for several values of solidity at $\beta = -5^\circ$ obtained from the DoE configurations used for the screening analysis by Morris method.



(a)



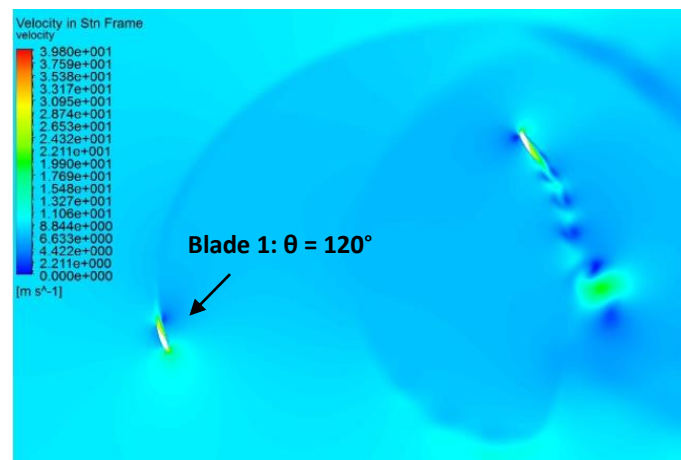
(b)

Figure 21. Influence of Solidity (σ) on the torque coefficient (C_t) of the wind turbine, $\beta = -5^\circ$: (a) $N = 2$; (b) $N = 4$.

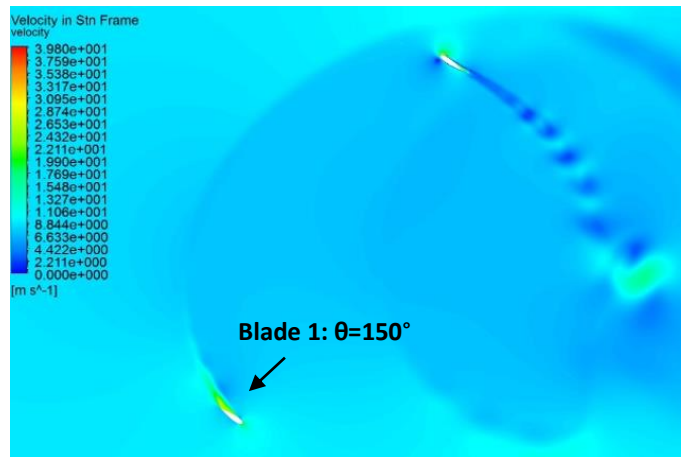
Figure 21b shows that for $\lambda = 2.63$, high solidity values do not provide higher efficiency loss, corroborating the results of Sungjun et al [63]. Furthermore, the analysis of Figure 21a

shows that for a solidity of $\sigma = 0.26$ the torque coefficient (C_t) decreases near $\theta = 50^\circ$, which does not occur for a solidity of $\sigma = 0.33$. These results are discussed based on flow dynamics shown in Figure 22, Figure 23 and Figure 24.

Figure 22 shows the existence of tracks on both blade 1 and blade 2 due to flow around the blades and formation of wake. The wake generated by blade 1 due to flow separation affects the performance of blade 2, disturbing the flow that reaches its leading edge. Figure 23 shows blade 2 immersed on this wake. This characteristic of flow is undesired in order to design high-efficiency VAWT.



(a) $\theta = 120^\circ$



(b) $\theta = 150^\circ$

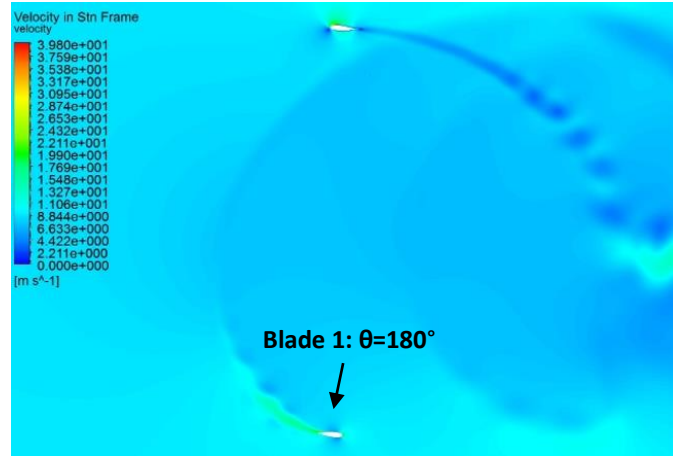
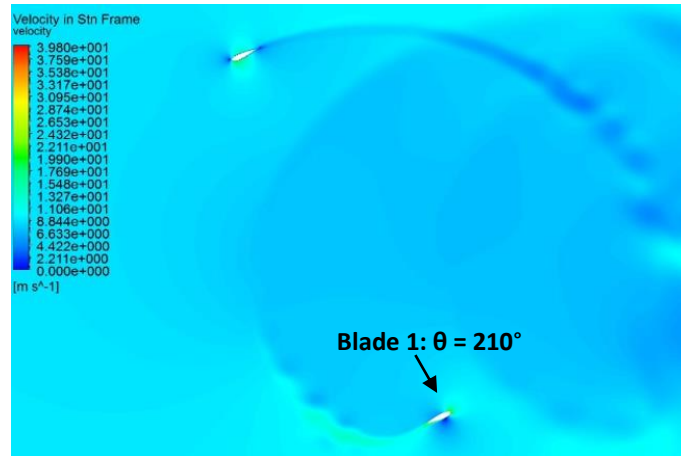
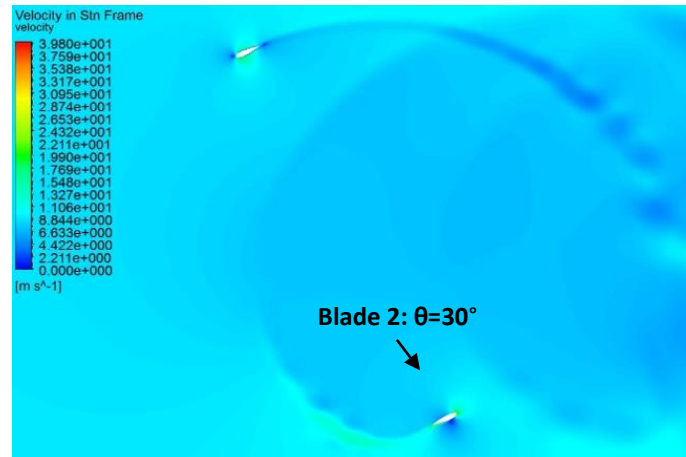
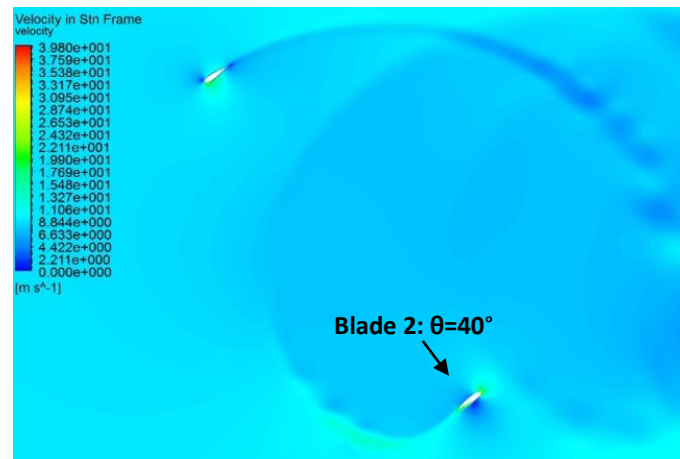
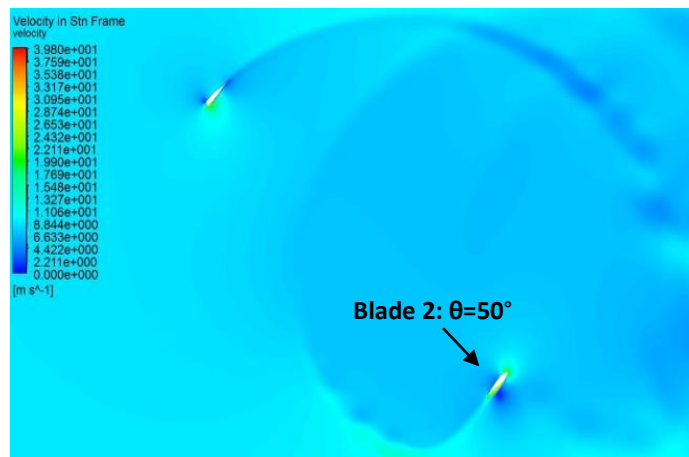
(c) $\theta = 180^\circ$ (d) $\theta = 210^\circ$

Figure 22. Velocity field highlighting tracks in the first study lap between $\theta=120^\circ$ and $\theta=210^\circ$ for a configuration $N=2$, $\beta=-5^\circ$ and $\sigma=0.26$.

(a) $\theta=30^\circ$ (b) $\theta=40^\circ$ (c) $\theta=50^\circ$

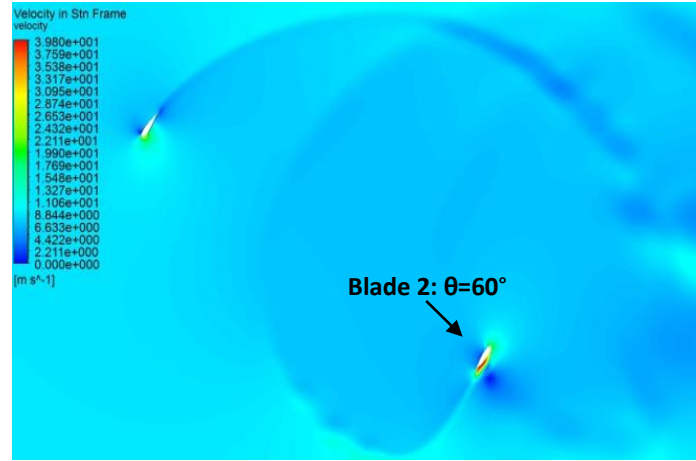
(d) $\theta=60^\circ$

Figure 23. Velocity field showing the interaction of blade 2 with the wake generated by blade 1 in the previous turn, $N=2$, $\beta=-5^\circ$ and $\sigma = 0.26$.

From Figure 21a, a loss of efficiency of the turbine is observed at $\theta = 50^\circ$, reaching a minimum C_t close to $\theta = 70^\circ$. Figure 24d shows a low-pressure zone on the profile upper surface at $\theta = 60^\circ$. Thus, at $\theta = 70^\circ$ (Figure 24f) occurs the vortex shedding at the trailing edge of the blade, reducing the lift due to pressure difference, which justifies the drop in the wind turbine performance.

At $\theta = 120^\circ$ (Figure 22a) the lift coefficient of blade 1 is decreasing while the drag coefficient of blade 2 is increasing. This phenomenon occurs until $\theta = 180^\circ$ when the lift coefficient of the entire turbine reaches a minimum value and drag coefficient is high enough. Nearby this point, the polar coefficient (C_l/C_d) of the turbine is minimum and consequently the torque coefficient (Figure 25) and the power coefficient reach their minimum values.

From Figure 23a, an increase in the drag coefficient of blade 2 follows the increase in the torque coefficient and power coefficient of the entire turbine consequently (Figure 25). This occurs because, in this moment, the lift coefficient of blade 1 is also increasing until $\theta = 40^\circ$ (Figure 23b). When the turbine reaches $\theta = 50^\circ$ (Figure 23c) and $\theta = 60^\circ$ (Figure 23d), maximum values of the drag coefficient of blade 2 cause a decrease in the torque coefficient (Figure 25), since the lift coefficient of blade 1 also starts to decrease. A decrease on C_l/C_d occurs.

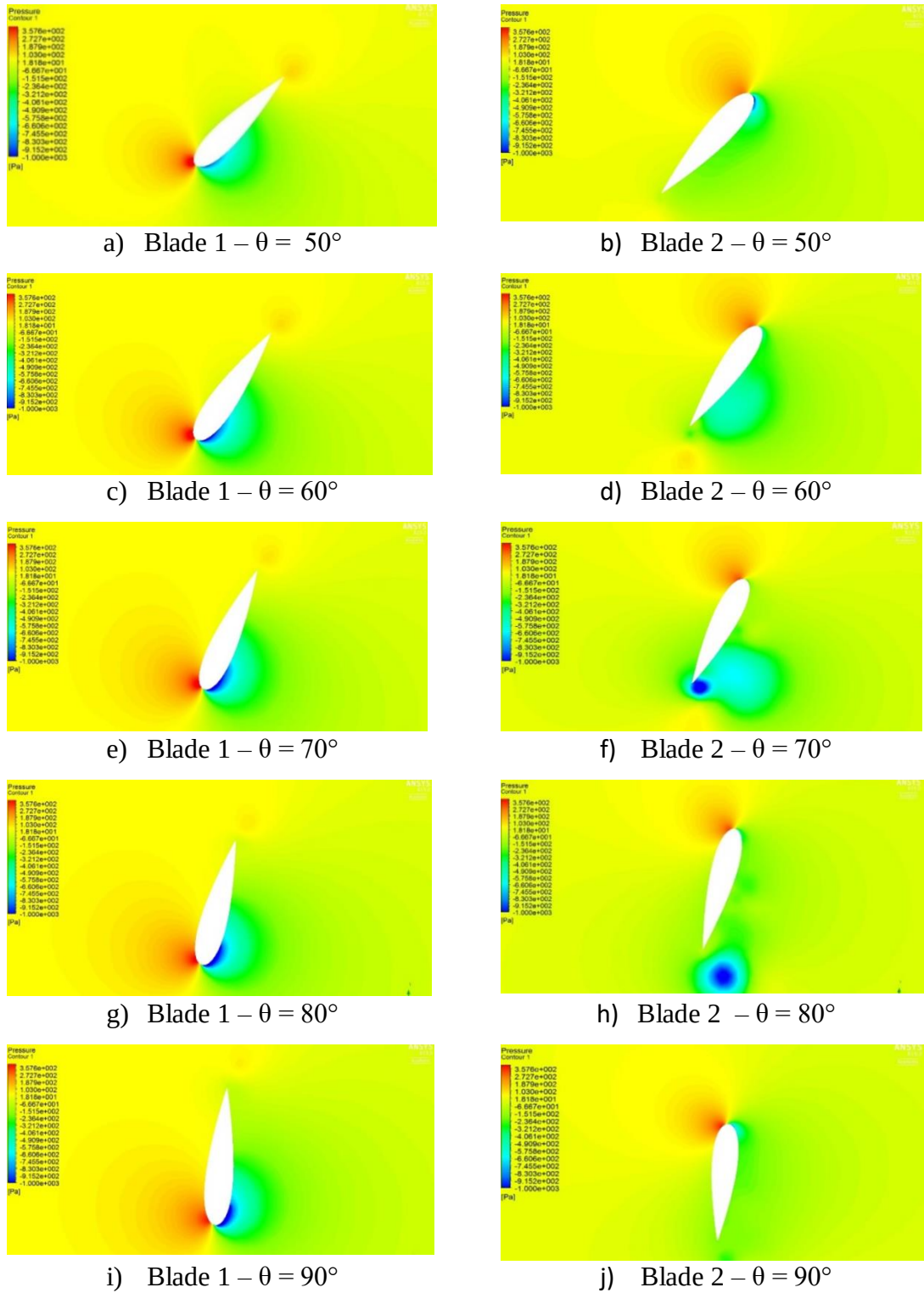


Figure 24. Pressure field for the NACA profile for a configuration with $N=2$, $\beta=-5^\circ$ and $\sigma=0.26$.

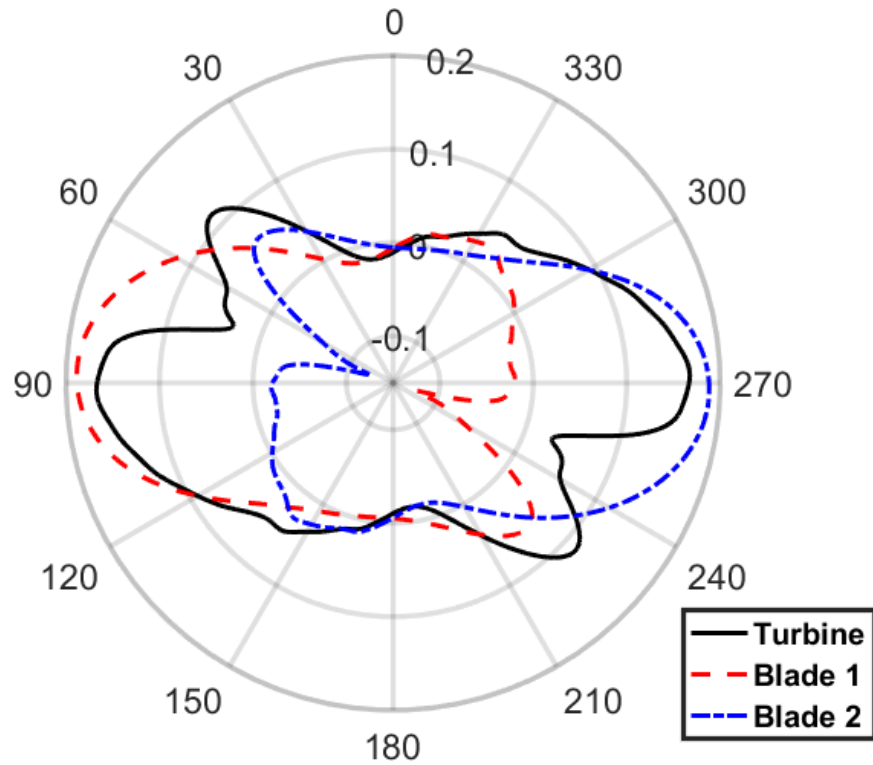


Figure 25. Turbine and per blade torque coefficient (C_t) in the last revolution for $N = 2$, $\beta = -5^\circ$ and $\sigma = 0.26$.

7. CONCLUSIONS

The present work performed the sensitivity analysis of four geometric parameters of a VAWT through the elementary effects method proposed by Morris. The sensitivity analysis was followed by an unconstrained optimization procedure by the NSGA-II methodology. The geometric parameters submitted to the sensitivity analysis and optimization were: number of blades (N), airfoil chord (c), turbine rotor diameter (D), and the pitch angle (β). The assumptions of two-dimensional, incompressible and turbulent flow for an unsteady flow were considered. This study focused on the analysis at $\lambda = 2.63$, since this value represents the maximum C_p of the base VAWT configuration according to previous experimental works. The major findings are summarized as follows:

- Sensitivity analysis from mathematic tools, such as Morris method, is a more powerful and friendly approach to evaluate the impact of several geometric parameters on the VAWT performance than conventional approaches through parametric analysis. This analysis also contributes to understanding the optimal VAWT configuration found by the optimization procedure;

- The screening analysis showed that the contribution rate of the pitch angle (β) on the power coefficient (C_p) is the highest among all input parameters, with a contribution of 58%. Although the parameters c , N , and D present a smaller influence on the power coefficient (C_p), together they present a representative influence on the wind turbine performance, which could be summarized by the solidity parameter.
- The optimal VAWT configuration increased the conversion efficiency by 40%, obtaining a power coefficient (C_p) of 0.42.
- Low energy conversion is observed for VAWT configurations that present flow separation, detachment of vortices and wake, causing loss of lift.
- The detailing of the influence of the pitch angle (β) showed that, for symmetrical profiles, the decrease in pitch angle up to $\beta = -3.3^\circ$ increases the turbine efficiency. On the other hand, the use of positive pitch angles decreases considerably the efficiency of the turbine, becoming null near $\beta = 4^\circ$.
- Regarding the influence of solidity (σ) on turbine performance, the range 0.4-0.6 leads to better turbine performance, obtaining maximum C_p at $\sigma = 0.5$. Furthermore, the phenomena involved for low solidity ($\sigma = 0.26$) was also investigated, showing that flow separation that occurs at the blade contributes less in C_t , thus promoting a drop in performance ($C_p = 0.17$), which is not as inefficient when compared to changing the pitch angle.

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