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Pitch angle impact on the aerodynamic performance of a straight-blade H-Darrieus turbine

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Abstract. *Due to the growing interest in wind energy in urban environments, vertical axis wind turbines (VAWTs) have received more attention. These have low installation and maintenance costs and can be installed in regions with large variations in wind direction. However, these devices still have lower power coefficients than horizontal axis wind turbines (HAWTs). For this reason, researchers are exploring ways to improve the efficiency of VAWTs by analyzing their aerodynamic performance. Pitch angle is a potential parameter to improve the performance of VAWTs. In this study, a 3-bladed straight H-Darrieus turbine with NACA 0022 symmetrical airfoils was used to investigate the variations of the power coefficient as a function of the top speed ratio and a detailed analysis of the flow field around the airfoils as a function of the tilt angle using computational fluid dynamics (CFD) calculations. Fixed tilt angles of -5°, -2.5°, -1.25° and 0° were investigated using Navier-Stokes (URANS) calculations with unsteady Reynolds mean and turbulence was modeled with the SST model* $\kappa - \omega$ *. The results indicate that an increase of approximately 50% in the mean value of the power coefficient can be obtained for an inclination angle of -5° at the optimum turbine operating point. These results are important to optimize the performance of VAWTs, contributing to the greater use of this technology for wind energy production in urban environments.*

Keywords: *Vertical axis wind turbine, Fixed pitch angle, Power coefficient*

1. INTRODUCTION

In recent years, there has been a significant increase in interest in wind energy and other renewable sources, driven by the need for energy diversification and awareness of the environmental impacts of fossil fuels Scungio *et al.* (2016); Danao *et al.* (2014); Kjellin *et al.* (2011). Wind energy has emerged as a promising alternative, as its generation capacity is not affected by political and economic instabilities Scungio *et al.* (2016); Bhuyan and Biswas (2014). The expansion of wind energy will contribute to greenhouse gas emissions reduction and the construction of a more sustainable and environmentally conscious future Bhuyan and Biswas (2014).

VAWTs present several characteristics that differentiate them from HAWTs. They are omnidirectional, have low installation and maintenance costs, produce low noise emissions, and perform well in turbulent flow conditions, making them suitable for urban environments Eriksson *et al.* (2008). Another notable aspect is the power density of VAWTs, which is higher than that of HAWTs Dabiri (2011). VAWTs are divided into drag-based rotors (Savonius) and lift-based rotors (Darrieus). The H-Darrieus rotor offers advantages such as high efficiency at low wind speeds and higher peak tip speed ratios (TSRs) compared to Savonius rotors Siddiqui *et al.* (2021).

Despite the aforementioned advantages, VAWTs have not dominated the wind turbine market due to their lower efficiency and lifespan compared to HAWTs Tummala *et al.* (2016). This issue arises from the aerodynamic complexity of VAWTs, such as the interaction between the blade and the wake Tescione *et al.* (2014), variation of the angle of attack at each angular position of the turbine during rotation, and the dynamic stall phenomenon. To optimize the performance of VAWTs, it is necessary to have a good understanding of these effects and develop effective control strategies Chehouri *et al.* (2015).

Research activities aimed at improving the performance and expanding the application fields of wind turbines have been growing steadily. To analyze the performance and flow characteristics around turbines, low-fidelity models based on momentum, such as the double multiple-streamtube model, are employed Paraschivoiu (2002). Additionally, potential flow models, cascade models, vorticity models, and vortex transport models are used as moderate-fidelity methods Wang and Yeung (2016); Ferreira *et al.* (2014); Islam *et al.* (2008). However, Computational Fluid Dynamics (CFD) simulation, a high-fidelity method, has become widely adopted in wind energy research. This approach provides more accurate information about the complete flow field around wind turbines, including aspects such as dynamic stall, compared to other models Paraschivoiu (2002); Ghasemian *et al.* (2017).

These methods have been employed to improve the performance of VAWTs, taking into consideration various parameters such as airfoil shape Bedon *et al.* (2016), solidity Maeda *et al.* (2016), and blade pitch angle Bianchini *et al.* (2015).

Among the mentioned parameters, the pitch angle (β) stands out as a promising option for optimizing the performance of VAWTs. This parameter is easily applicable in practice and does not involve high manufacturing, installation, or maintenance costs Rezaeiha *et al.* (2017). Rezaeiha *et al.* (2017) concluded that a pitch angle of -2° is ideal for their H-Darrieus turbine, resulting in a 6.6% increase in the power coefficient at a TSR of 4.4. On the other hand, Sun *et al.* (2021) determined that a pitch angle of -4° was ideal for their H-Darrieus turbine with 3 and 5 blades. A power coefficient increase of 5.89 times was achieved for the 5-blade turbine, while a maximum increase of 5.14 times was obtained for the three blades turbine.

In this article, 3D Reynolds-averaged Navier-Stokes (URANS) simulations will be conducted, validated through experiments performed by Howell *et al.* (2010), aiming to analyze the effect of a fixed pitch angle on the power coefficient curve relative to the TSR. The simulations were performed for pitch angles of -5°, -2.5°, -1.25°, and 0°. As a result, it was defined that the pitch angle of -5° is optimal for the three TSR analyzed. With an increase of approximately 50

2. WIND TURBINE MODEL

This section contains all the parameters used to perform the numerical simulation, such as geometry data, mesh topology, and boundary conditions.

2.1 VAWT modeling

Figure 1 shows the CAD model of the fixed pitch VAWT turbine. The H-Darrieus turbine is composed of three blades built with the airfoil profile, NACA 0022. The diameter (D) of the turbine is 0.6 m, the blade chord length is 0.1 m, and the power rating is 11.79 W. The wind velocity (V_∞) is 4.31 m/s.

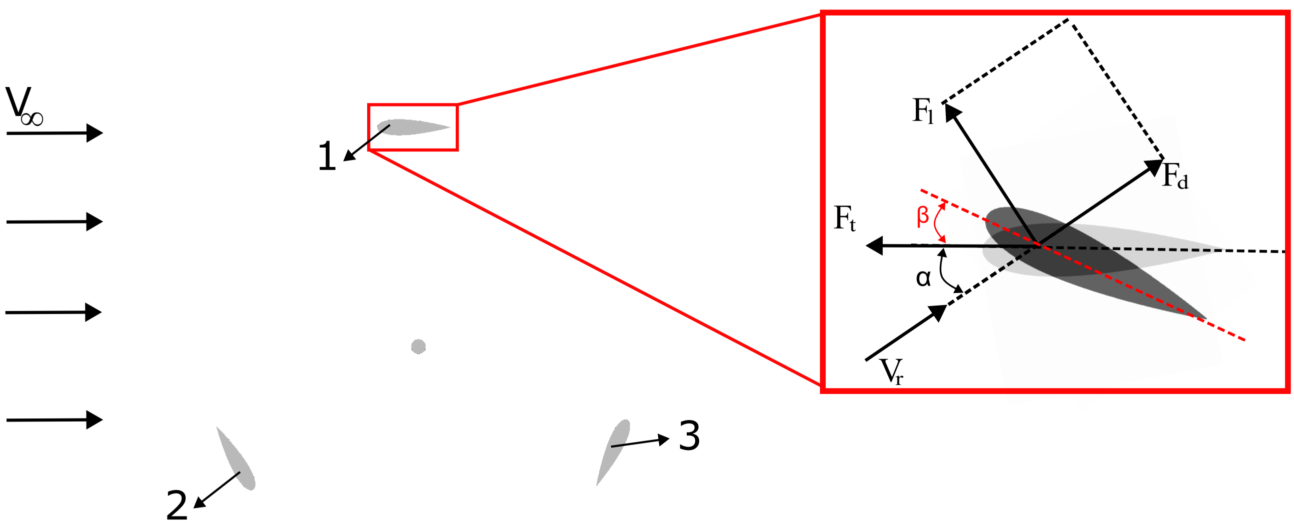

Figure 1. H-Darrieus turbine and parameters of the article problem. Unperturbed flow of uniform profile, V_∞; Pitch angle, β, has influence on the power produced.

Figures 2 and 3 depict the geometric model of the turbine positioned within a cylindrical domain to enable the turbine's rotation during the transient simulation. The cylindrical domain is situated within another static domain with a length of $18R$ and a width of $8R$, with R represents the radius of the turbine. The coordinate system's center is located at the top of the turbine's central axis, with x representing the streamwise direction and y representing the cross-stream direction.

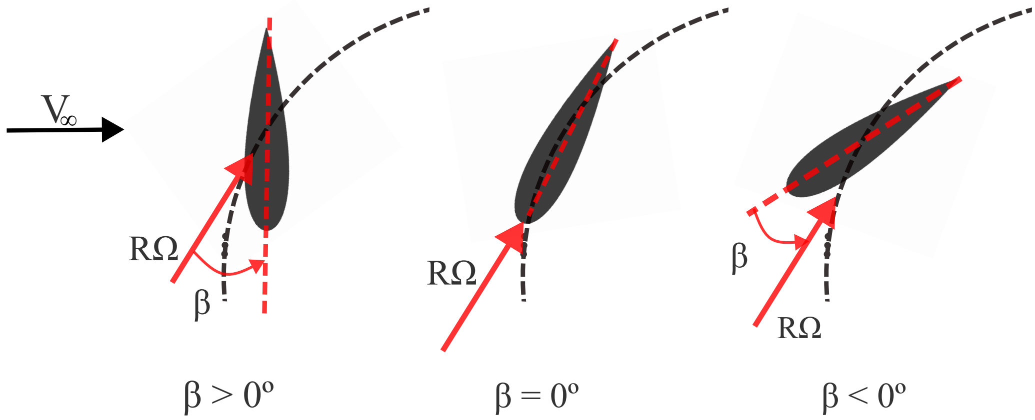

Figure 2. Schematic representation of a blade with three different pitch angles: positive, zero and negative.

Table 1. Turbine geometrical data.

Parameters	Valeus
Diameter (m)	0.6
Chord length (m)	0.1
Number of blades	3
Inlet velocity (m/s)	4.31
Blade profile	NACA 0022

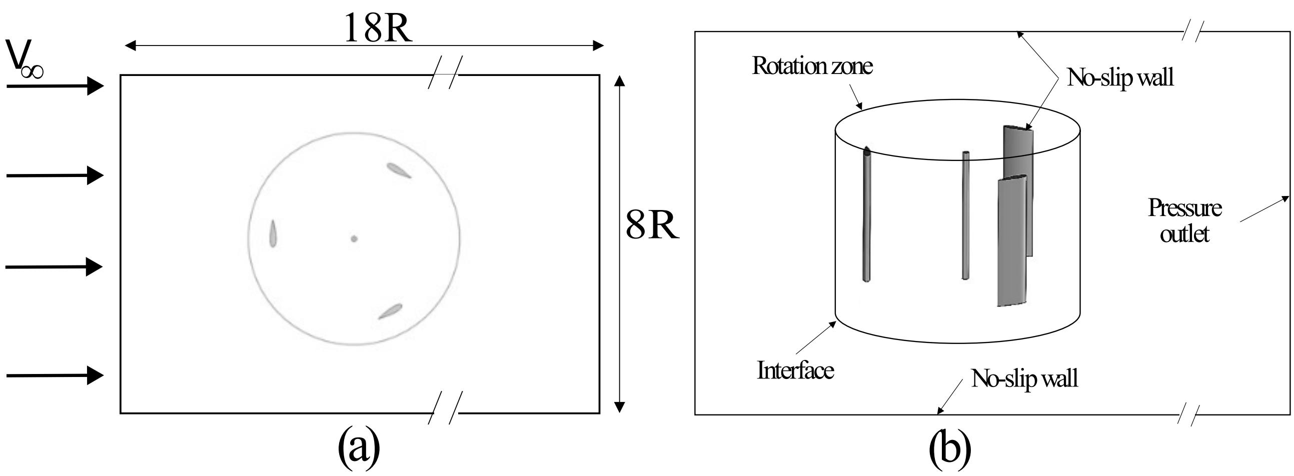

Figure 3. (a) Top view schematic of the computational model. (b) Wind turbine, flow domain, and boundary condition. The rotation zone is discretized using a sliding mesh

2.2 Mesh generation and optimization

To obtain high-quality special discretization, the two domains had their meshes generated separately but consistently in the interface zone. In addition, the Sliding Mesh Rotating technique was applied in the interface zone, which allows modeling rotational effects in the rotational domain (rotor). The mesh around the airfoils was created using the inflation tool, which models the region near the wall, to have a better description of the boundary layer, with 15 levels in the boundary layer of the airfoils, with the first layer having a height of $5.6 \times 10^{-5} m$ so that $y^+ = 1.45$ and with a growth rate of 1.1. The rotational domain contains a mesh with 1,696,915 nodes, The mesh of the static domain contains 119,071 nodes. Within this mesh, a refinement was made in the wake region and the interface zone close to the rotational domain to maintain the spatial discretization refinement and accurately reproduce the interaction between the wake and the blades.

2.3 Boundary conditions and solver setup

This study uses the implicit model equations (URANS) with the turbulence model Shear Stress Transport (SST). The corresponding boundary conditions are applied to the computational model. The upper, lower, front, and back boundary conditions receive slip conditions. The left side of the static domain has an inlet velocity condition of 4.31 m/s, turbulent

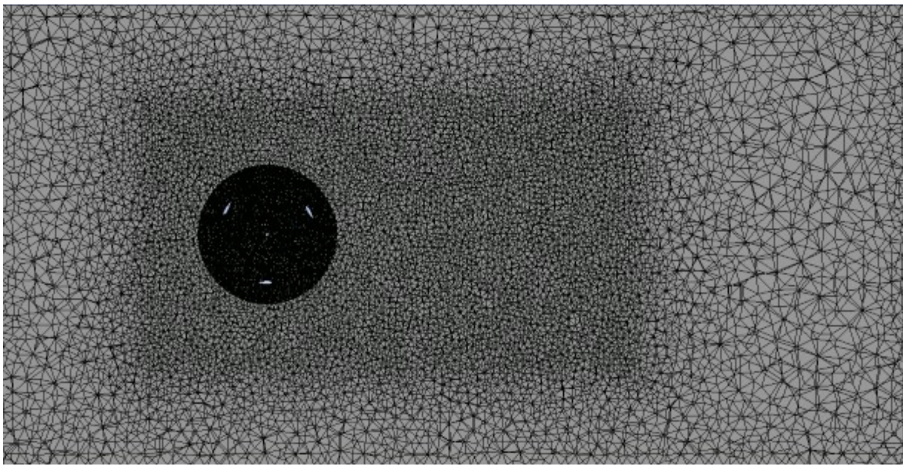

Figure 4. A numerical mesh is used to simulate the turbine. The total number of nodes in the mesh was 1,815,986.

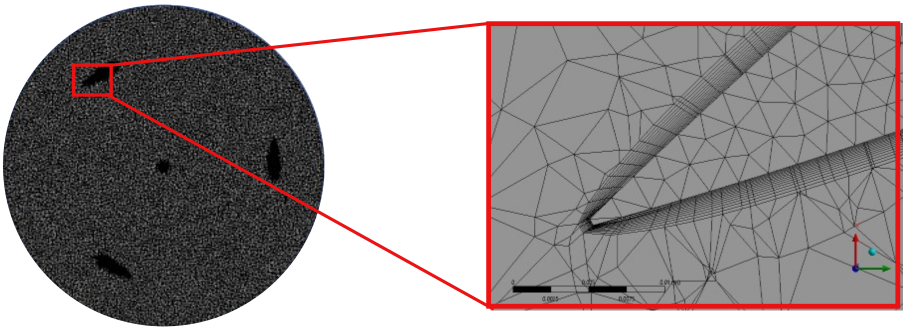

Figure 5. Mesh refinement in the rotating domain with inflation applied to the blades.

intensity of 1% and length scale of 0.01. The right side has an outlet condition assigned with a static pressure of 0. The geometric structure of the turbine is applied as a non-slip boundary condition. In the rotating domain, as illustrated in Figure 3, it undergoes circular motions according to the blade tip velocity ratio. For this study, three TSR points were analyzed: 1.34, 1.87, and 2.2. The area where the two domains meet exhibits an interface condition.

Transient analysis with an azimuthal increment of 3.6° was employed for all three TSRs analyzed. To achieve an azimuthal increment of 3.6°, a specific time step was defined for each TSR. For $TSR = 1.34$, the timestep was 0.0034 seconds, for $TSR = 1.87$, the timestep was 0.0022 seconds, and finally, for $TSR = 2.2$, the timestep was 0.0020 seconds.

The convergence of the simulation was checked using the power coefficient (C_p). To reach the steady state, 5 complete revolutions of the turbine were required, for a total simulation time of 36 hours. After entering the steady state, two more revolutions were simulated, but only the data of the last revolution were recorded and stored; for these two revolutions, 16 hours of simulation were required.

The simulations were carried out at the Energy and Environment Laboratory (LEA) of the University of Brasília (UnB), using version R21.1 of the ANSYS CFX software on equipment with the specifications shown in Table 2

Table 2. Computer specifications

Processor	Intel Xeon E5-2643 3.50 GHz
Number of processors	2
Number of cores	24
RAM memory	64 GB

3. RESULTS

The performance of a given turbine is measured through the variation of torque and power coefficient (C_p) as a function of the tip-speed ratio. The torque variation refers to the value produced by the turbine blades in one rotation. The expression for C_p is defined as

$$C_p = \frac{T\omega}{0.5\rho A_S V_\infty^3}, \tag{1}$$

where T is the torque value in (N.m), ω is the rotation speed in (rad/s), A_S is the swept area in (m²), V_∞ is the wind speed in (m/s), and ρ is the density of the air in (kg/m³).

The tip speed ratio (TSR) of a wind turbine is expressed as the ratio between the rotation speed of the rotor blade tip and the (V_∞), that is, $TSR = \omega R / V_\infty$ where R is the value of the rotor radius. Therefore, VAWT's performance is heavily dependent on its TSR value.

To validate the simulation, the article by Howell (2010) was used. The operating point of the turbine, $TSR = 1.87$, was used as a comparison. Table 3 compares the value obtained in the simulation with the values found by Howell in his 3D simulation and experiment.

Table 3. Comparison of values found by Howell *et al.* (2010) for a $TSR = 1.87$. Values show C_p.

	C_p
Howell *et al.* (2010) 3D model	0.1859
Howell *et al.* (2010) Experimental	0.1764 $\pm 20\%$
Current	0.1778

Figure 6 shows the average C_p value for the three TSRs and the four pitch angles analyzed. Based on the results, a significant increase in the average C_p is observed for the pitch angle variations compared to the 0° pitch case. The turbine, when the blades have a pitch angle of -1.25°, had its optimal TSR changed from 1.87 to 2.2. The -5° pitch angle showed the highest increase in C_p among the four analyzed cases.

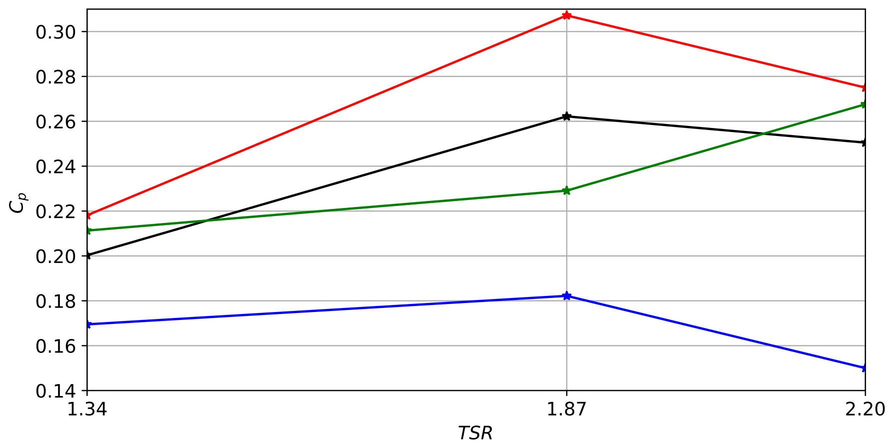

Figure 6. Graph shows the results found for the average C_p at each pitch angle analyzed. (——) -1.25°, (——) -5°, (——) 0° and (——) -2.5°.

3.1 Vorticity field analysis

By analyzing Figure 7, we can observe that in the blade 2, when the $TSR = 1.34$ and the pitch angle is -5°, there is a delay in the vortex separation compared to the 0° pitch. In the case of $TSR = 1.87$, at the 0° pitch blade, there is an increase in the thickness of the positive vorticity region in the intrados compared to the -5° pitch case. This increase in thickness indicates a proximity to the dynamic stall phenomenon. In the case of $TSR = 2.2$, the problem of increased thickness in the intrados region of blade 2 is still present. In addition, it is important to note that blade 3, with pitch of 0°, does not present the vortex separation phenomenon observed with pitch of -5°.

4. CONCLUSION

The objective of the study was to compare four pitch angles to determine which has the greatest influence on the turbine's C_p at three points on the TSR. To obtain the results, a 3D URANS simulation was performed to analyze the C_p of the turbine and the effects of varying the pitch angle on the vorticity field.

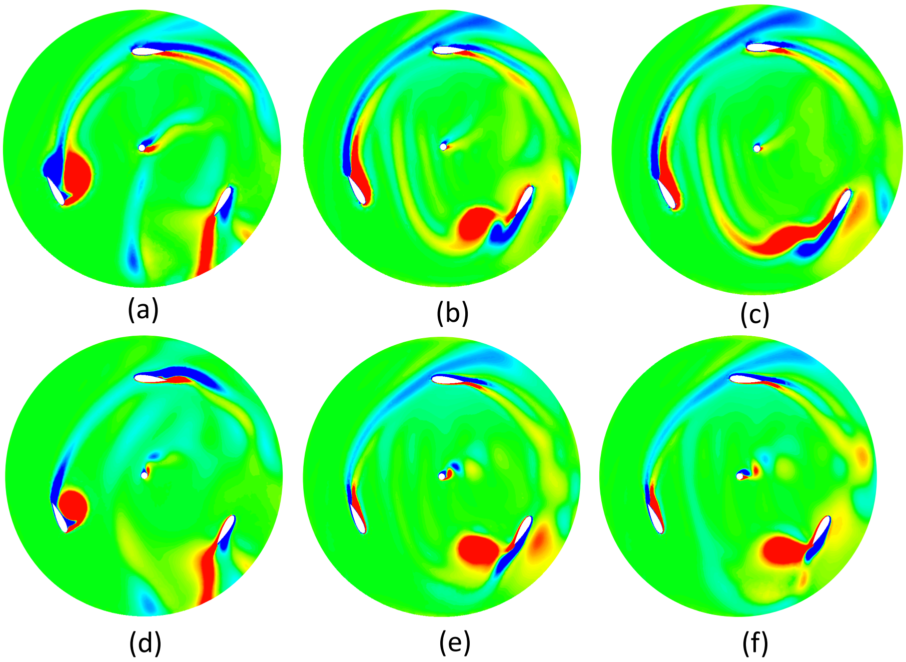

Figure 7. Represents the vorticity field for pitch angles of 0° and -5°, respectively. (a, d) 1.34, (b, e) 1.87, and (c, f) 2.2.

Firstly, it was observed that a pitch angle of -1.25° resulted in a change in the optimum operating point from a TSR of 1.34 to 2.2. This shows that the choice of pitch angle can have a significant impact on wind turbine performance, opening up opportunities for optimization.

In addition, it was evident that the pitch angle of -5° resulted in the greatest increase in the power coefficient (C_p) at all points analyzed. This significant increase in C_p indicates that the pitch angle plays a critical role in improving the efficiency of a VAWT, making it more competitive with HAWTs.

When analyzing the vorticity field, we observed notable differences in the effects between pitch angles of -5° and 0° in the three TSR values analyzed. This suggests that the pitch angle not only affects the C_p, but also has a direct impact on the flow dynamics around the turbine blades.

This study makes important contributions to improving the performance of VAWTs. The analysis of the pitch angle proves to be a critical factor in improving the efficiency of these turbines and, therefore, the feasibility of their wider adoption in wind power generation.

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