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The Impact of Increasing the Number of Undulations in the Undulatory Shape Distributed Along the Concave Surface of a Savonius Wind Turbine Blade Inspired by the Flower of Life Concept

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Abstract. In our latest research, we investigated the incorporation of an undulatory pattern along the concave surface of Savonius turbine blades. This study builds upon our previous findings, where we examined the effects of varying undulation counts across four distinct shapes (with radius of 22 mm, 30 mm, 60 mm, and 80 mm), while maintaining consistent overall blade dimensions. To analyze the aerodynamic performance, we employed the unsteady Reynolds-Averaged Navier-Stokes (RANS) equations in conjunction with the Shear Stress Transport (SST) k-ω turbulence model, using ANSYS Fluent software. In the current study, the number of undulations was increased by approximately 50%, resulting in a total of 60 points along the blade profile. This enhanced configuration was validated using recent numerical data to assess its impact on the moment and power coefficients of the turbine across a range of tip speed ratios (TSRs). All simulations were conducted under consistent conditions, including a 15% overlap ratio relative to the rotor diameter and an inlet wind velocity of 7 m/s. This study shows that the MODEL80 exhibited the highest power coefficient value of 0.277.

Keywords: CFD, power coefficient, Savonius, undulations, wind turbine.

1 Introduction

In response to the growing threat posed by the reliance on fossil fuels and their associated carbon dioxide (CO_2) emissions—recognized as a major contributor to environmental degradation and climate change—researchers have increasingly focused on identifying alternative energy sources capable of reducing greenhouse gas outputs [1, 2]. Among these alternatives, wind energy has emerged as a promising and sustainable solution, with wind turbines offering significant potential to curtail CO_2 emissions and support efforts to maintain global temperature levels within environmentally sustainable limits.

Wind turbines are broadly categorized into two main types: horizontal-axis wind turbines (HAWTs), which are well-known for their high energy generation efficiency [3], and vertical-axis wind turbines (VAWTs), which traditionally produce lower power output [4]. However, it is important to recognize the trade-offs associated with each type. HAWTs typically require large land areas, specific wind orientations, and substantial investment for installation and maintenance [5]. In contrast, VAWTs, while offering comparatively lower energy output, are advantageous in urban and space-constrained environments due to their ability to capture wind from multiple directions and their lower installation and maintenance costs [6].

The Savonius wind turbine has gained attention primarily due to its structural simplicity, which allows for easy installation on buildings in both urban and rural environments. This type of VAWT is particularly effective at operating under low wind conditions, with a cut-in wind speed as low as 2.5 m/s [7]. Despite these advantages, the Savonius turbine generally exhibits lower energy conversion efficiency compared to conventional three-bladed HAWTs [8].

The power coefficient (Cp) of the Savonius turbine typically ranges between 0.15 and 0.25, depending on the wind speed and operating conditions. Due to its relatively modest performance in capturing and converting wind energy, ongoing research efforts are focused on exploring innovative design modifications and optimization strategies to enhance the aerodynamic efficiency and overall power output of the Savonius turbine.

The power coefficient of VAWTs can be significantly improved by optimizing various parameters, including overlap ratio, blade thickness, rotor diameter, and the number of blades [9]. Additionally, a range of geometric features—such as end plates, blade shapes, bucket configurations, and multi-stage rotors—have been shown to influence power coefficient values, as highlighted in previous studies [10].

These parameters play a critical role in the aerodynamic performance of Savonius wind turbines, making blade design optimization a key area of focus for researchers. The primary objective is to identify an optimal blade configuration that maximizes energy conversion efficiency. Numerous studies have therefore explored different strategies for refining blade geometry, with the dual goal of enhancing positive static torque while simultaneously reducing negative static torque throughout the turbine's rotation cycle.

Extensive research has been conducted in the field of VAWTs, with each study employing distinct optimization strategies to improve turbine performance. In the work presented by [10], the authors analyzed the effects of varying blade counts and TSRs on turbine efficiency. Their results indicated that a three-bladed Savonius configuration yielded the highest performance, with optimal efficiency observed at a TSR of 0.555 under an inlet wind velocity of 7 m/s. Another notable study comes from *Marouane et al* [11], who introduced an innovative design concept inspired by the geometric "flower of life" pattern. Their approach involved incorporating an undulating profile along the concave side of the Savonius blade, derived from the aforementioned geometric motif. The study examined four different undulation radii—22 mm, 30 mm, 60 mm, and 80 mm—across a range of TSRs from 0.5 to 1.2. Among these, the 60 mm radius (MODEL60) demonstrated the most significant enhancement in performance when compared to the conventional Savonius turbine design, particularly at a TSR of 0.7 and 1 at an inlet velocity of 7 m/s.

Zemamou et al [12] reported an optimal Cp value of approximately 0.35, representing a 29% improvement over the Cp value typically observed in conventional Savonius wind turbines. In their study, the researchers utilized Bezier curve techniques to model the convex and concave sections of the turbine blades, leading to enhanced aerodynamic performance. Similarly, *Sanusi et al* [13] conducted an experimental investigation on a modified Savonius wind turbine, incorporating a hybrid blade design that combined a conventional circular-shaped blade with a concave elliptical blade. Their findings revealed a significant 11% increase in the Cp value compared to the conventional blade model, with the improvement most notably observed at a TSR of 0.79.

In our recent study, we explored how the undulating pattern along the concave surface of the blades contributed to an improvement in the power coefficient. In contrast, the current investigation aims to assess the effect of increasing the number of undulations along the concave surface and how this modification may influence the power coefficient. In the previous study, it was observed that the maximum power coefficient was attained at a TSR of 1 across all four models. Therefore, in the present study, we focus on analyzing the variation in the power coefficient for each configuration specifically at TSR = 1, as this operating condition was previously verified to yield the highest performance.

2 Rotor configuration / Computational domain / boundary conditions

The rotor diameter of SWT is defined by the configuration of two semi-cylindrical blades. Blades rotating in the direction of the incoming flow are termed advancing blades, while those moving against the flow are referred to as returning blades. Numerous studies have proposed design modifications to the SWT with the aim of enhancing its power coefficient [8, 10]. The key difference between our previous study and the current investigation lies in the number of undulations integrated into the blade geometry. **Figure 2** provides a comparative analysis of the two design configurations.

Figure 1 illustrates the computational domain employed in this study, which is identical to that used in our recent publication. Similarly, the boundary conditions summarized in **Table 1** are consistent with those previously applied. This alignment ensures a reliable and credible comparative analysis of the influence of the number of undulations on aerodynamic performance across both studies.

The grid independence test and simulation methodology employed in this study are consistent with those utilized in *Marouane et al* [11] work. Given the repetitive nature of these procedures, we have chosen to reference the methodological approaches from *Marouane et al* [11] study, as they are identical to those applied in the current investigation

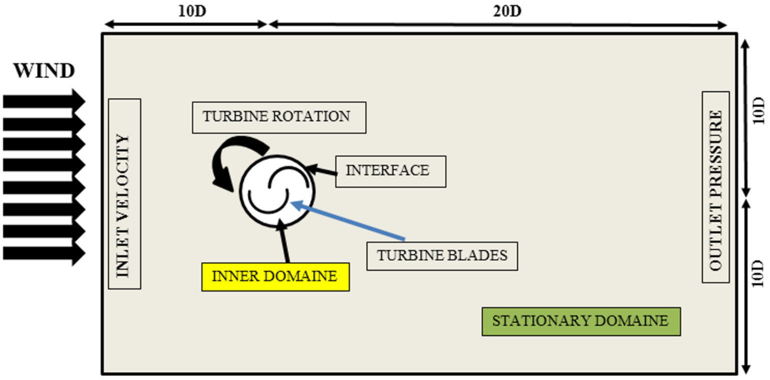
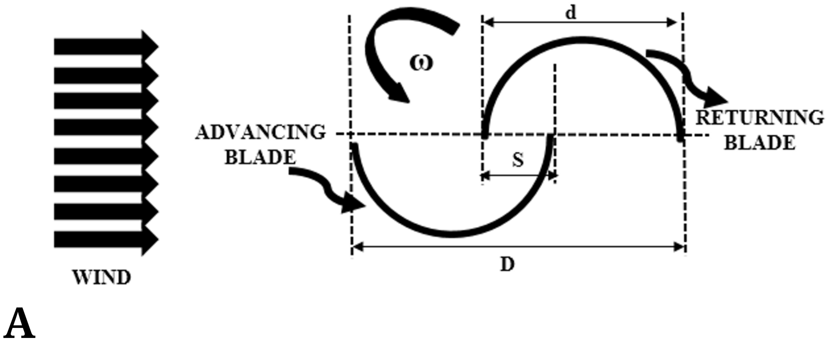


Figure 1. Computational Domain. [11]

Table 1. Boundary conditions. [11]

Parameters	Inputs
Inlet	Velocity-inlet
Outlet	Pressure outlet
Upper wall	Symmetry
Lower wall	Symmetry
Turbine	Rotating body (no slip)
Interface	Interface between stationary and rotating zones



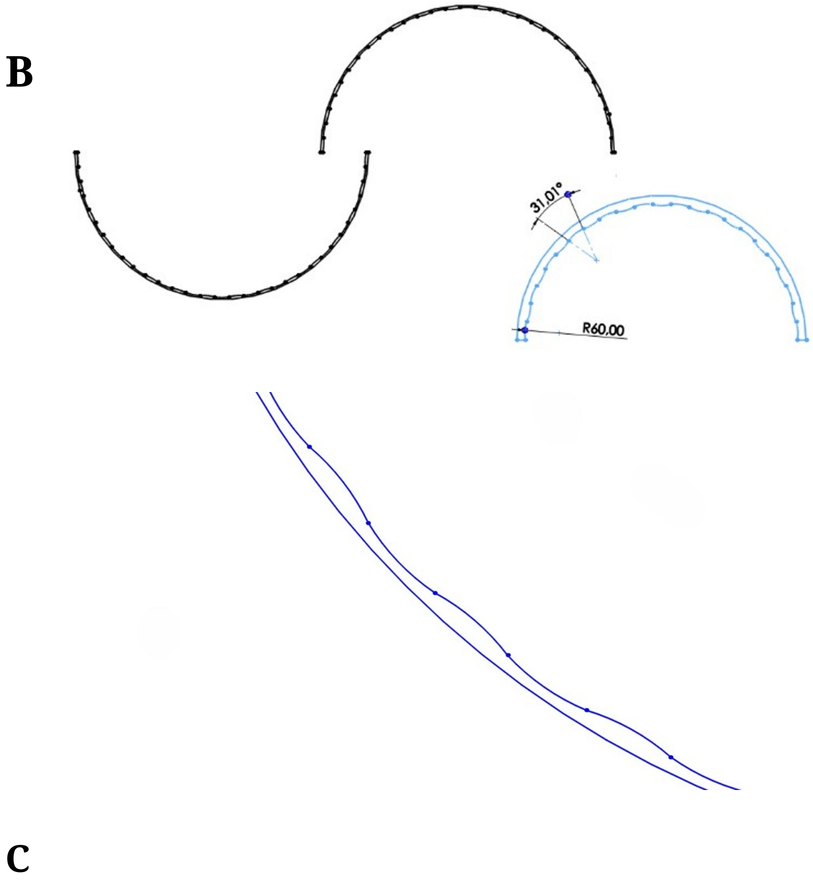


Figure 2. A) Conventional SWT; B) Undulatory configuration; C) Zoom-in.

3 Equations and Mathematical Expressions

In the analysis of VAWT dynamics, it is beneficial to employ a turbulence model that discretizes both kinetic energy and its dissipation, especially when computational cost is a limiting factor. This is particularly important in scenarios involving incompressible, unsteady, and turbulent fluid flow. In our case, where computational resources are constrained to a system with only two processing cores, the **k–ω SST** turbulence model emerges as the most appropriate choice due to its balance between accuracy and computational efficiency. The conservation equations are presented as follows:

The continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla(\rho u)=0 \qquad (1)$$

The momentum equation:

$$\frac{\partial u}{\partial t}+u\nabla u-\vartheta\nabla u=-\frac{1}{\rho}\nabla\rho+g \qquad (2)$$

The evaluation of the effectiveness of a SWT might be characterized by two fundamental parameters: the moment coefficient (Cm) and the power coefficient (Cp), that are inextricably linked with TSR. The TSR is a variable that is linked to the rated wind speed and the diameter of the rotor. It may be determined by dividing the speed of the blade tip by the speed of the airflow going through the blade.

$$TSR=\lambda=\frac{V_{rotor}}{V}=\frac{\omega R}{V} \qquad (3)$$

The torque and power coefficient can be defined as follows:

$$C_p=\frac{P_{turbine}}{P_{wind}}=C_m\lambda \qquad (4)$$

$$C_m=\frac{M}{M_{wind}}=\frac{M}{0.5\,\rho AR\,V^2} \qquad (5)$$

To address the complexity of the flow, particularly under unsteady conditions, it is essential to employ numerical simulations for solving equations (1) and (2). These equations must be discretized using appropriate numerical techniques. The effectiveness of such methods largely depends on the computational software employed. In this study, ANSYS Fluent was used as the simulation tool, applying the finite volume method (FVM) to convert the governing partial differential equations into algebraic equations. The solution process was carried out using an iterative approach based on the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm.

4 Results & Discussion

4.1 Results convergence

The performance of a SWT is primarily governed by the pressure, drag, and lift forces acting on its blades [14]. These aerodynamic forces vary in response to changes in the angle of attack of the rotor blades. The orientation of the blades along their rotational paths is determined by their angular positioning, which results in varying blade geometries influenced by the direction and strength of the wind. Each of these geometrical configurations exhibits a distinct set of aerodynamic force coefficients. Consequently, the torque produced by a Savonius rotor fluctuates with the rotational angle due to the continuous variation in force coefficients throughout the blade's motion. Additionally, this torque is influenced by the rotor's rotational speed, as it alters the relative wind velocity experienced by the blades, thereby affecting the effective angle of attack and the corresponding aerodynamic force coefficients [15].

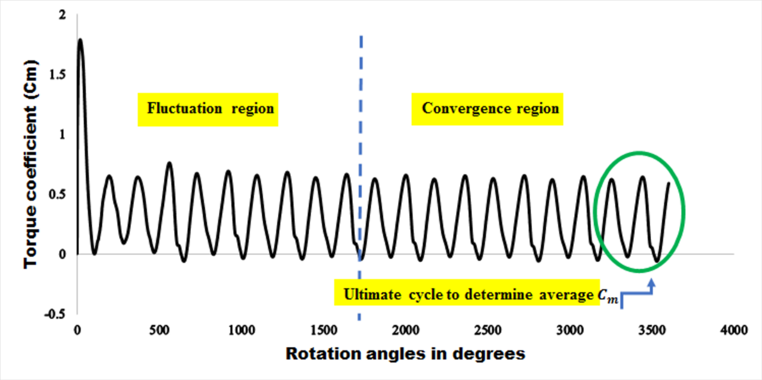


Figure 3. Torque coefficient for 10 rotations at a TSR of 1. [11]

The torque coefficient of the rotor was analyzed across various rotational angles, as illustrated in **Figure 3**. This analysis presents the temporal evolution of Cm for a TSR of 1. Initially, a prominent peak in the Cm values is observed, followed by irregular fluctuations in the subsequent peaks. This instability can be attributed to the use of an inappropriate initial condition—specifically, the assumption of a uniform inflow velocity of 7 m/s across the entire computational domain. However, as the simulation advances into the second series of rotor steps, the Cm values begin to exhibit a more consistent and periodic pattern, indicating the development of a stable and convergent solution.

4.2 Undulatory shape of 60 points vs 30 points

As stated at the outset, this study investigates the effect of increasing the number of undulations on the aerodynamic performance of the rotor. **Figure 4** highlights the differences between the blade geometry employed in *Marouane et al* [11] previous study and that used in the current investigation. The results demonstrate a consistent improvement in performance across all four geometries compared to the previous design. **Table 2** presents a comparison of the power coefficient values from both studies. For a TSR of 1, the power coefficient is equivalent to the moment coefficient, as defined in Equation (4).

In contrast to the previous study, the influence of an increased number of undulations is observable in the present results (Table 2). While the differences between the configurations are modest, the **MODEL80MM** design suggests a positive trend in the power coefficient compared to the **30-point** design. These findings indicate that the number of undulations, in addition to the radius, plays a role in the turbine's aerodynamic response. To ensure the robustness of these observed trends, the potential influence of numerical sensitivity—including mesh parameters and discretization—was considered. While the current results align with established physical trends in the literature, further high-precision sensitivity studies regarding round-off and discretization errors would provide an even more refined confirmation of these performance gains.

Table 2. A comparative analysis of the average power coefficient C_p between the current and recent study.

Numerical Studies	Numerical model	Power Coefficient C_p **TSR=1**			
		Model 22MM	**Model 30MM**	**Model 60MM**	**Model 80MM**
Model of 60 points	SST k-omega	0.262	0.269	0.273	0.277
Model of 30 points	SST k-omega	0.260	0.265	0.272	0.266

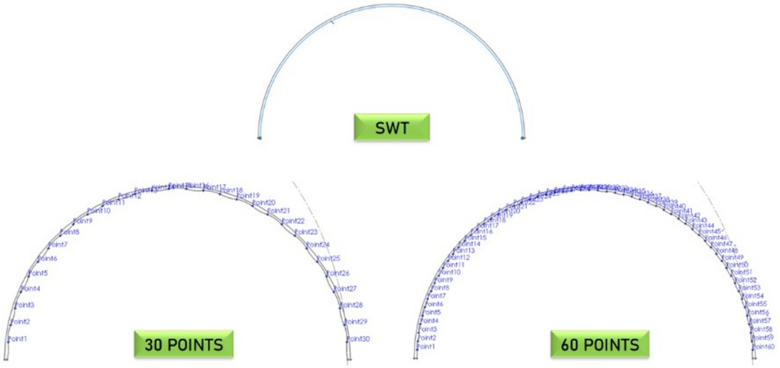


Figure 4. Undulatory pattern for both geometries.

4.3 Analysis of flow patterns

As in our recent study, we presented pressure distributions, streamlines, and velocity vector contours to compare the conventional SWT design with the optimized **MODEL60** configuration. The previous study highlighted significant differences in pressure and velocity variations along both surfaces of the blades—particularly the advancing blade. In contrast, the current investigation demonstrates that increasing the number of undulations leads to an improved design, with **MODEL80** (comprising 60 points) emerging as the optimal configuration

This enhancement is supported by the velocity vector contours, which reveal a marked difference between the conventional **SWT**, **MODEL60** with **30 points**, and **MODEL80** with **60 points**. **Figures 5, 6,** and **7** illustrate the distribution of velocity vectors along the convex surfaces of the blades. The magnified sections clearly depict regions of reversed flow, particularly along the blade surfaces. Among the compared configurations, **MODEL80** exhibits the smallest reversed flow region—potentially negligible when compared to both **MODEL60** and the conventional SWT.

These findings corroborate the results of our previous study, reinforcing the hypothesis that blade undulations play a crucial role in mitigating reversed flow along the blade surfaces. Reversed flow regions are indicative of substantial flow separation, which contributes to increased drag and a consequent decline in aerodynamic performance.

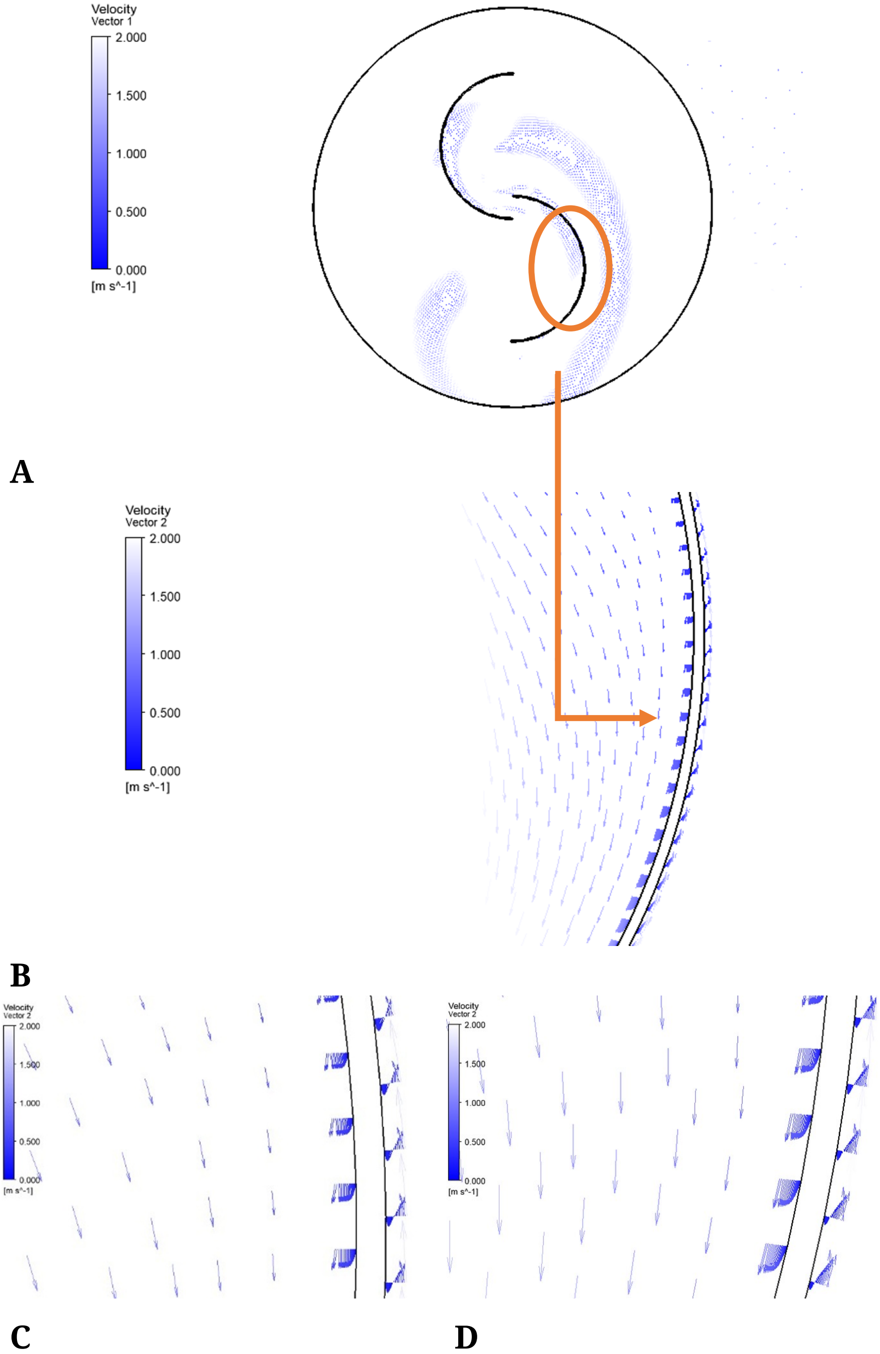


Figure 5. A) Velocity vectors of conventional SWT, [B, C, D] Zoom-In.

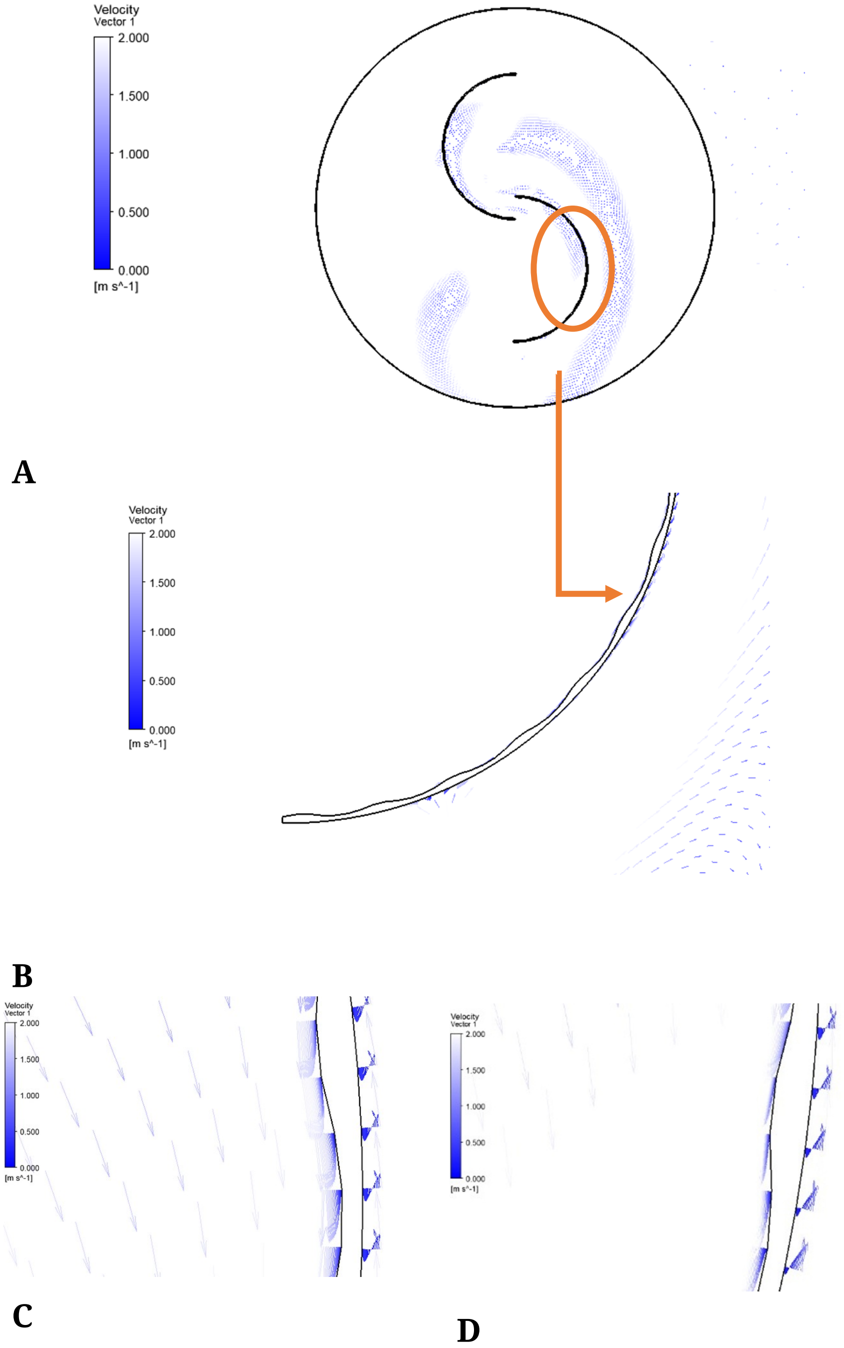


Figure 6. A) Velocity vectors MODEL60 (30 points), [B, C, D] Zoom-In.

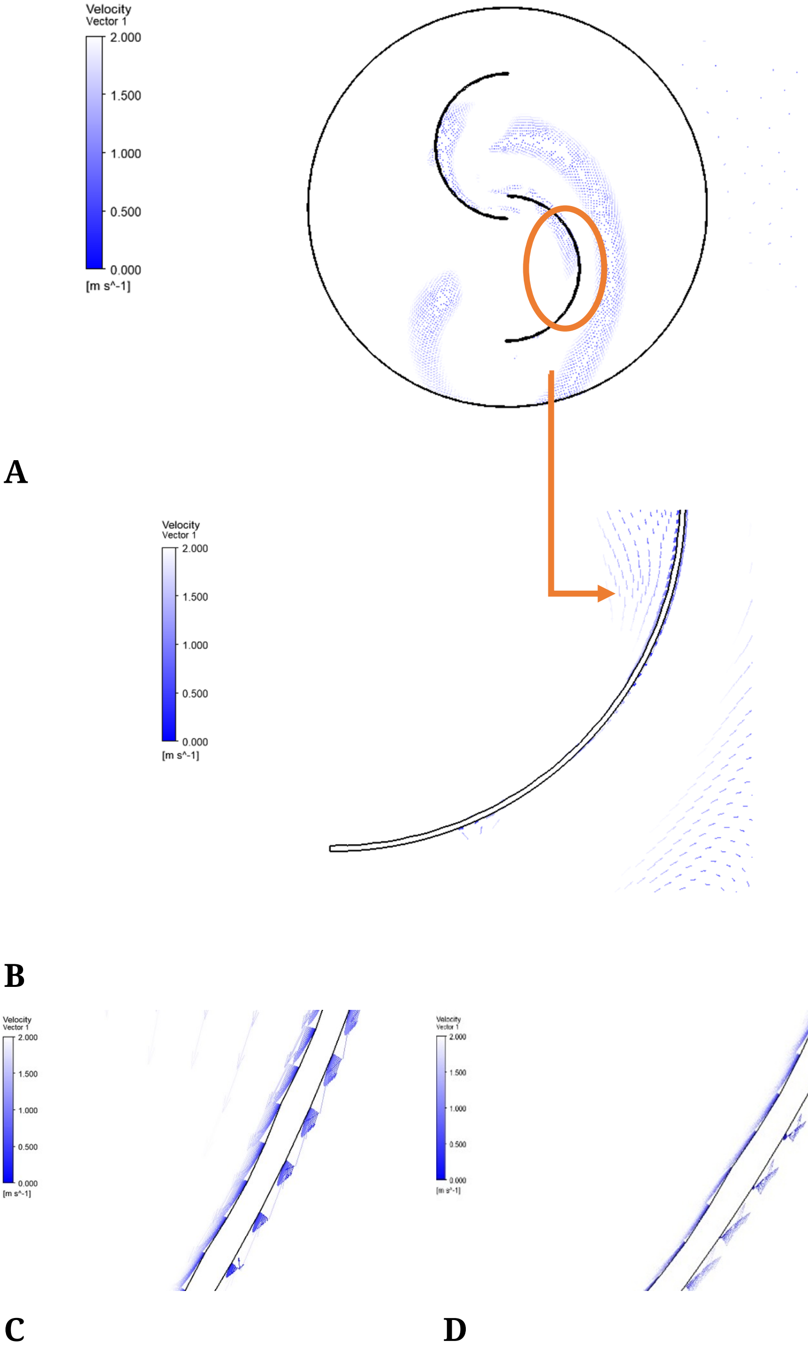


Figure 7. A) Velocity vectors MODEL80 (60 points), [B, C, D] Zoom-In.

5 Conclusion

A two-dimensional numerical investigation was carried out using a novel methodology involving an increased number of blade undulations. Building upon prior research, this study focused on examining the effects of these undulations along the concave surfaces of the blades. The results indicate that the undulations not only influence the flow behavior around the concave surfaces, but also significantly affect the flow dynamics along the convex surfaces, as evidenced by the velocity vector distributions.

In addition to well-established design parameters such as blade thickness, overlap ratio, and rotor diameter, the introduction of surface undulations represents a novel design strategy. This approach, inspired by the geometric concept of the "flower of life," offers potential for identifying an optimal undulation pattern that can enhance the power coefficient of the turbine, thereby improving its overall aerodynamic efficiency.

Future work will involve a more detailed investigation aimed at determining the optimal configuration for this class of vertical axis wind turbine, with the objective of maximizing performance through refined undulation design.

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