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Blending Airfoils: An Innovative Approach to improve the Aerodynamic Performance of a Vertical Axis Wind Turbine

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Abstract

The increasing demand for sustainable and renewable energy sources has led to a growing interest in wind energy, particularly in densely populated regions like Bangladesh. VAWTs offer distinct advantages over traditional horizontal axis turbines, including ease of installation, operation in turbulent winds, and suitability for urban environments. The VAWTs, particularly the Darrieus type, are turbines that can efficiently capture wind energy in a wide environment, making them suitable for Bangladeshi conditions. This work aims to analyze different NACA airfoil profiles and their modified configurations that can be used in 3.5 kW H-type Darrieus VAWTs by numerically investigating their aerodynamic performance. Using Ansys Fluent with a transient k-ω SST model, the study examined the aerodynamic characteristics of the wind turbine at a Reynolds number, velocity, and tip speed ratio of 2×10^6, 10 m/s, and 2.5. Primarily, the numerical simulation was conducted on three base profiles, NACA0015, NACA0021, and NACA23015, to determine their coefficient of power (C_P). Amongst them, the 5-digit cambered profile NACA23015 was chosen as the primary profile to be further modified by blending its suction surface or its pressure surface complementarily with the other one of those two 4-digit profiles. Subsequently, a total of four new configurations are obtained. The maximum value of C_P among them was 0.33257 for the configuration with the suction surface of NACA23015 and the pressure surface of NACA0015, which is higher than that for any other considered profile. Also, as previously mentioned, the pressure side of the NACA23015 used for modification resulted in degraded performance; this indeed pointed out that camber distribution is a very critical factor in the efficiency of a VAWT. The satisfactory findings from this study can be used to further optimize the design of airfoils in Darrieus VAWTs, encouraging other researchers to conduct modification adopting similar methodology.

Keywords: Aerodynamic performance, CFD, Blending airfoils, TSR, VAWT

1. Introduction

Since the cities of Bangladesh are densely populated and the availability of land is limited, vertical-axis wind turbines (VAWT) can be considered a more promising alternative approach to decentralized energy production in comparison with large-scale horizontal-axis wind turbines. Concerning the growth of energy demands and the potentiality of wind energy development in the coastal/offshore areas of the country[1], [2], optimization in the design of VAWTs may thus contribute significantly to sustainable energy solutions [3]. During the last couple of years, VAWTs have attracted considerable attention from researchers due to their efficiency in harnessing wind energy in both urban and offshore environments. Compared to their horizontal-axis variant, VAWTs are considered advantageous due to their omnidirectional acceptance of wind, reduced noise, and easier installation and maintenance. Amongst various configurations of VAWTs, the Darrieus configuration alone has received much attention because of its higher aerodynamic efficiency, especially the possibility of generating more energy at a wide range of wind velocities [4]. However, the operating efficiency of the Darrieus VAWT is exceptionally dependent on the aerodynamic characteristics of the airfoil profiles used [5]. In recent studies, much emphasis has been put on the optimization of airfoil profiles to improve the power coefficient (C_P) of a turbine to increase the overall efficiency of the turbine [6]. This present study adds to the growing body of literature by testing various airfoil profiles and examining new modifications that have the potential for further performance optimization.

The classical way of representing the aerodynamic performance of a wind turbine is the power coefficient C_P, i.e., the ratio of the mechanical power output of the turbine to the power carried by the wind through the swept area [4]. Because of the unique operating mechanics, Darrieus VAWTs exhibit unsteady aerodynamics and are burdened with certain obstacles in achieving high efficiencies. Most of the research pointed out the importance of choosing appropriate airfoil profiles for Darrieus VAWTs since their aerodynamic performances can be highly

dependent on the characteristics of the selected airfoils, namely thickness, camber, shape of the suction and pressure surfaces, varying lift-to-drag ratios, flow separation behaviour, and susceptibility to unsteady aerodynamic effects such as dynamic stall [4], [6]–[8].

In recent years, NACA airfoil profiles have been extensively studied in the context of VAWTs by the researchers. These profiles are well-documented, so they are popular choices when studies of wind turbine performances and optimizations are performed [9]. Three baseline airfoil profiles are considered in this paper: NACA0015, NACA0021, and NACA23015. NACA0015 and NACA0021 are symmetric airfoils but with different thicknesses. These profiles are standard and used for HAWT and VAWT applications [10]–[12]. NACA23015 is a cambered 5-digit airfoil that has proved to possess better lift characteristics than its symmetric counterpart. Numerous published studies reveal the influence of such airfoil profiles on the performance of VAWTs. For example, Eriksson et al. (2008) demonstrated that thicker symmetric profiles, such as the NACA0021 perform better for lower tip-speed ratios due to structural stability, while thinner ones, such as the NACA0015, do well for higher tip-speed ratios due to the flow around the airfoil being attached and therefore creating less drag [13].

Wing blade and/or profile modification to enhance the aerodynamic performance of the H-type Darrieus VAWT is one of the most trending research topics amongst researchers in recent years [4]. Chen et al. (2015) introduced a novel J-blade (blade with open suction surface) which lowered the power coefficient, however, increased the coefficient of static torque [14]. The V-blade of Su et al. (2020), on the other hand, has not only improved the power output, the structural integrity of the wind turbine also improved [4]. Other researchers have found satisfactory aerodynamic performance enhancements by adding split flap in the trailing edge [7], winglet, gurney flaps and many other modification techniques [4]. However, as per the best knowledge of the authors of this study, no study has been conducted so far on the profile modification by blending the traditional baseline airfoils by complementarily selecting their pressure and suction surface. The main goal of this study is to investigate and demonstrate the potential of airfoil modification through this type of camber blending as a method for improving the aerodynamic performance of a 3.5 kW H-type Darrieus VAWTs, i.e.; how different combinations of suction and pressure surfaces can influence turbine efficiency, and developing a foundation for future numerical as well as experimental work aimed at validating these findings under real-world conditions.

2. Model and Methodology

In the study conducted by Zhang et al., the researchers focused on analyzing a 3.5 kW Vertical Axis Wind Turbine (VAWT) model that was initially developed by Tullis et al. [15], [16]. This VAWT utilized the NACA0015 airfoil blade, depicted in **Fig. 1(a)**. This study's primary objective was to investigate the blending of different airfoil profiles to enhance the performance of the VAWT model. To achieve this, we selected three specific NACA airfoils from two distinct categories. These included two four-digit symmetric airfoils - NACA0015 (used in the VAWT model) and NACA0021 (a thick airfoil), as well as a five-digit asymmetric airfoil, NACA23015 (shown in **Fig. 1**). It's important to note that the study focused on a specific Tip Speed Ratio (TSR) value of 2.5, intending to identify an optimal blended airfoil profile that would deliver improved performance and efficiency within this specific TSR range. The original VAWT model by Tullis et al. [16] achieved a maximum power coefficient (C_P) of 0.317 at TSR = 2.5, making this the optimal TSR value for the VAWT when operating at a wind velocity of 10 m/s. For the purpose of improving performance in this specific TSR, the study delved into a blending process that entailed modifying the upper and lower cambers of each airfoil. This process resulted in the creation of four blended profiles: NACA23015 (upper camber) +NACA0015 (lower camber) (M1), NACA0015+NACA23015 (M2), NACA23015+NACA0021 (M3), and NACA0021+NACA23015 (M4), as visually represented in **Fig. 1**. The study numerically evaluated seven airfoil profiles, including the three primary profiles (NACA0015, NACA0021, NACA23015) and the four blended profiles mentioned above.

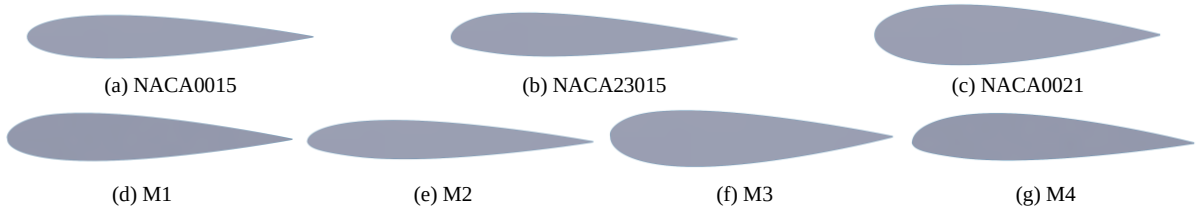


Fig. 1. Different profiles for VAWT blade.

The computational domain with dimensions was utilized according to Balduzzi et al.'s method [17] and adopted from Zhang et al.'s work [15] Boundary conditions are depicted in **Fig. 2**, where D is the turbine diameter (2.5m). The domain has been fragmented into three distinct zones: Outer stationery domain, Rotating domain, and Inner stationary zone. The Sliding Mesh Method (SMM) was utilized to simulate 2D VAWT with three blades in ANSYS Fluent. Hence, each zone was connected by a mesh interface. In the study by Zhang et al., they did not

take into account the rotor shaft. However, it's important to note that the rotor shaft is an integral part of the turbine, and its aerodynamic impacts can affect the entire flow field and the performance of the VAWT [15].

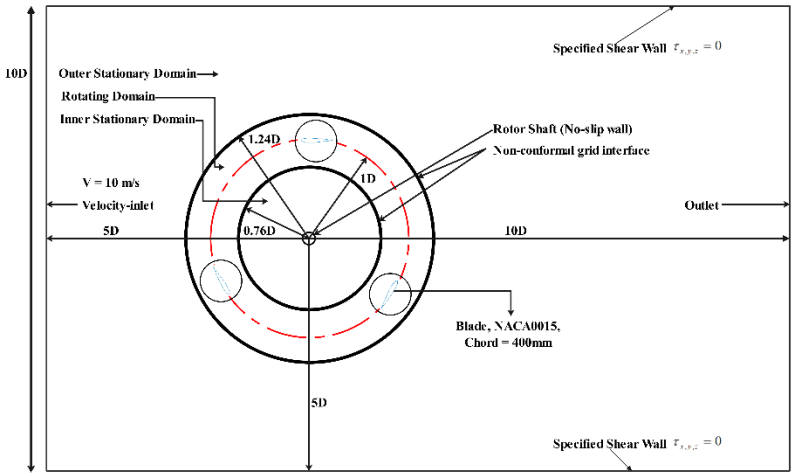


Fig. 2. Schematic of the whole domain.

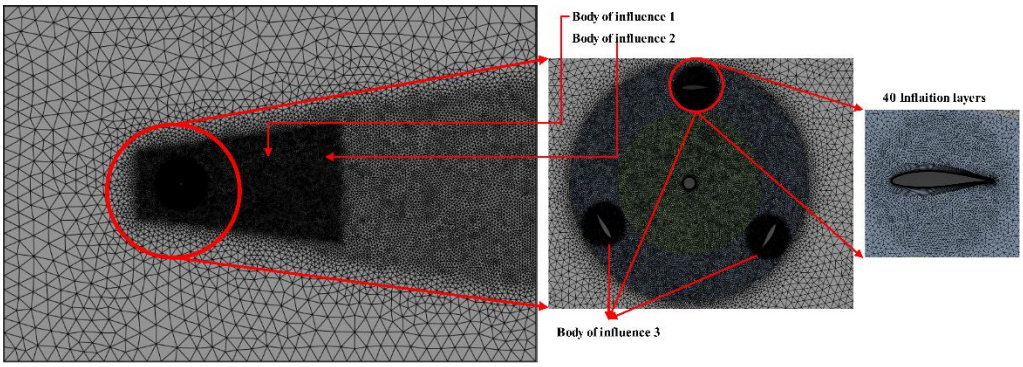


Fig. 3. Schematic for grid distribution.

In our study, we made a deliberate decision to include the effects of the rotor shaft. We used 2D Unsteady Reynolds-averaged Navier-Stokes (URANS) equations, specifically employing the k-ω SST turbulence model to numerically solve the problem. All the necessary governing equations for the k-ω SST turbulence model can be found in Menter's work [18], [19]. Double precision was used for all simulations, and compressibility effects were assumed to be negligible. Consequently, the Pressure-based solver was used for the simulations. The inlet wind velocity was adjusted to 10 m/s while maintaining the turbine rotational speed (ω) constant at 20 rad/s. As suggested by Balduzzi et al., instead of using SIMPLE and PISO schemes, in this study, coupled schemes were utilized. Moreover, second-order accurate schemes for spatial discretization and a Bounded Second Order Implicit scheme for time discretization were used [17]. The least squares cell-based gradient was employed, and hybrid initialization was used to minimize errors. For the unsteady simulation, the time step size was set to 0.0008722, maintaining a CFL value of less than 0.8722. The time step size was calculated using $\Delta t = \frac{\pi D}{360 \omega R}$, for degree rotation per time step.

Table 1. Overview of the critical parameters used in the numerical investigation.

Parameter	**Value/type**	**Parameter**	**Value/type**
Analysis type	Transient	Reference values	Compute from inlet
Viscous model	k-ω SST model		Area- 2.5 m^2
Fluid velocity	10 m/s		Length- 1.25 m
Reynolds number	2×10^6	Method	Pressure Velocity
Boundary conditions	Inlet-velocity inlet		Couple Scheme
	Outlet-pressure outlet		2^{nd} order
	Top, Bottom Wall-Free slip	Moving Mesh	Sliding Mesh Method
	Blade wall-No slip	Angular Velocity	20 rad/s
Number of zones	3	Time step size	0.0008722

The maximum iteration per time step was set to 30, all residuals convergence criteria was set below 1e-5. The mesh plays a substantial role in the SMM simulation; hence, each zone has to be discretized according to the requirement. In the generated mesh, the blade profile had 40 inflation layers and a Y+ value was almost 0.14142. Moreover, the rotating and inner stationary domains have an element size of 2e-2m, and the outer domain has an element size of 1m. Two bodies of influence (0.1m and 0.2m) were used around the rotating domain to produce a fine mesh, and an extra body of influence (1e-2m) for each of the three blades was generated to capture flow characteristics accurately. **Fig. 3** represents the mesh of the SMM domain for 2D VAWT. **Table 1** shows the numerical simulation setup summary.

3. Validation

A comparison was made between our findings and the experimental and computational results reported by Zhang et al. in order to validate the Computational Fluid Dynamics (CFD) simulation results for the NACA0015 airfoil (**Fig. 4**) [15]. As determined experimentally, the coefficient of power (C_P) for the NACA0015 airfoil was stated in the referenced research to be 0.317. In the same study, their CFD simulation produced a slightly higher value of 0.345, corresponding to an error of approximately 8.8%. In contrast, the power coefficient obtained from our CFD simulation was 0.306, with a minor error of 3.47%. This slight deviation can be explained by several things, such as variations in the simulation's boundary conditions, grid resolution, and numerical techniques. Slight underprediction of aerodynamic coefficients is common in CFD simulations since the model might not accurately represent the complexities of real-world flow, such as turbulence and boundary layer effects, especially at crucial points on the airfoil. However, the discrepancy between the experimental value (0.317) and our numerically obtained C_P (0.306) is negligible, suggesting that the CFD model offers a reasonably realistic depiction of the flow mechanics for the NACA0015 airfoil. Our CFD approach for estimating the aerodynamic performance of the NACA0015 airfoil has been validated by its close agreement with both the experimental data and the computational results of the reference research.

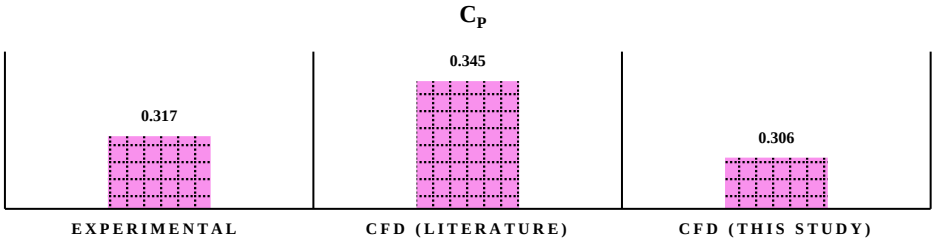


Fig. 4. Validation of C_P values with literature.

4. Result and Discussion

The experimental value for NACA0015 from the study done by Zhang et al. [15] is compared with the coefficient of power (C_P) values derived from the CFD study of different airfoil profiles, including blended airfoils (Note, TSR = 2.5 for all cases). NACA0015 has a C_P value of 0.306, which is very close to the experimental value shown in **Fig. 5**. NACA0021, and NACA23015 generate C_P = 0.311, and C_P = 0.3095, respectively. The blended profile M1 produces the highest C_P = 0.33257, suggesting a considerable improvement in aerodynamic performance. A higher C_P indicates that the turbine is more efficient at capturing wind energy and converting it into mechanical energy. The combined profile M3 yields a coefficient of power C_P = 0.29, as shown in **Fig. 5**, which might perform better at different TSR value. Moreover, the M4 blend profile produces a C_P of 0.25, and the lowest performance was produced by the M2 combination. Mainly, it was due to the fixed TSR (2.5) value of the current study, as different blade has different optimal TSR values [20].

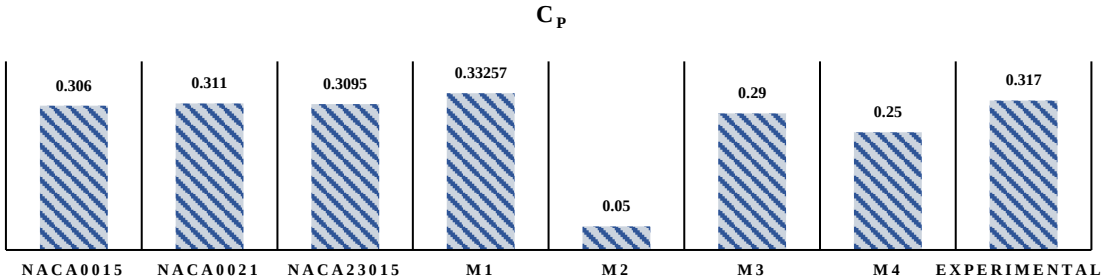


Fig. 5. Coefficient of Power (C_P) of Different Profiles

Fig. 6 illustrates the variation of torque coefficient (C_T) with respect to the azimuthal angle (θ) for several airfoil profiles. Every curve illustrates how well the corresponding airfoil or blended design performed during the wind turbine's complete 360° revolution. The torque coefficient oscillates between positive and negative values as the blades rotate, corresponding to the fluctuations in the angle of attack of each blade. We have chosen to narrow our focus to only five blade profiles to conduct a more in-depth analysis and provide a more comprehensive characterization. This approach allows us to make detailed comparisons between the different profiles and better understand their individual characteristics and performance. Among all the airfoil profiles investigated, the M1 configuration demonstrates the maximum peak torque coefficient, reaching approximately 0.277. Additionally, this arrangement shows a more uniform torque distribution over the course of the rotation cycle with the lowest negative peaks, suggesting improved aerodynamic efficiency and energy production. With a peak C_T near 0.258, M3 exhibits slightly lower peak torque values than the M1 combination. In contrast, the NACA0015 and NACA0021 individual airfoils show moderate peak torque values accompanied by more noticeable changes during the azimuthal cycle, perhaps resulting in less steady energy output. NACA23015 shows a similar trend to M3. The torque coefficient at which the turbine can overcome mechanical resistance and produce useful power is directly related to its peak torque. Higher peaks indicate better performance, especially when there is little wind. These results demonstrate how blending airfoils, in this case NACA23015 with NACA0015, dramatically increases the turbine's aerodynamic efficiency by generating more torque and stabilizing energy output.

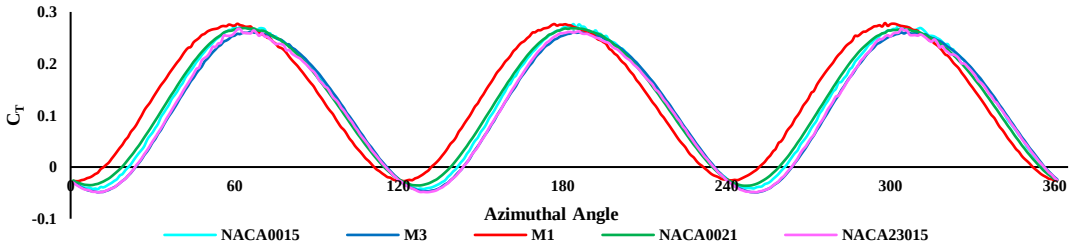


Fig. 6. Torque coefficient (C_T) vs Azimuthal Angle

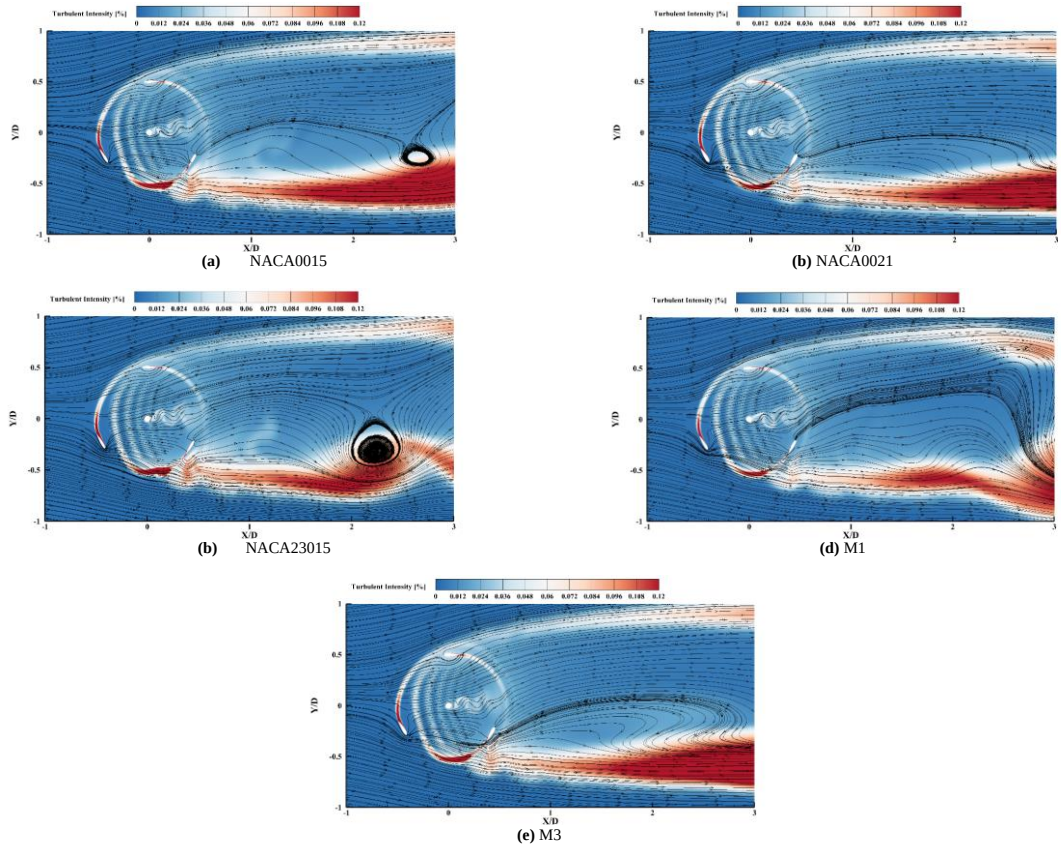


Fig. 7. Turbulence intensity of the flow field of different airfoil profiles

Fig. 7 illustrates the turbulent intensity of the flow field around different types of airfoil profiles. NACA0015 and NACA23015 profiles both exhibit vortex formation in their flow field. The red region indicates the highest

turbulence intensity. M1 shows the lowest turbulence intensity compared to other profiles. Excessive turbulence, especially in the trailing edge region, can lead to flow separation, reduce lift, and increase drag. Ultimately, these factors can significantly impact the power output and efficiency of the wind turbine. In this case, the M1 profile demonstrated the best performance. Additionally, the NACA23015 profile shows less turbulence intensity compared to other pure NACA series profiles, indicating its potential for improved aerodynamic performance.

5. Conclusion

This study has successfully investigated the aerodynamic performance of a 3.5 kW H-type Darrieus VAWT by numerically testing various NACA airfoil profiles and their modified configurations. Among these, the configuration where the upper camber of NACA23015 combined with the pressure surface of NACA0015 gave the maximum coefficient of power of 0.33257, which is higher than the other considered configurations for the tip speed ratio of 2.5. On the other hand, using the NACA23015 profile as the pressure surface in modifications generally reduced performance, pointing out the critical role that camber distribution plays in airfoil efficiency. While these results suggest the potential for improving the aerodynamic performance of H-type Darrieus VAWTs through blending airfoil profiles, further optimization is necessary to establish a reliable foundation for this approach. This entails conducting numerical investigations across a broad range of TSR. Future research endeavors may concentrate on fine-tuning these airfoil modifications and validating their performance through experimental testing. This could provide valuable insights into enhancing the efficiency and effectiveness of H-type Darrieus VAWTs.

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