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Research Article

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Posted Date: October 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10876459/v1>

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Additional Declarations: No competing interests reported.

Aerodynamic Enhancement of a Horizontal-Axis Wind Turbine Using Backward-Facing Aero-Shaped Vortex Generators

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Abstract. The aerodynamic performance of horizontal-axis wind turbines (HAWTs) is severely constrained by flow separation on the blade surfaces, particularly at low wind speeds and high angles of attack. Separation causes a critical loss of lift and a sharp increase in drag, markedly reducing energy extraction efficiency. This study examines the application of backward-facing, aero-shaped vortex generators (VGs) as a passive flow control strategy to mitigate these detrimental effects. High-fidelity computational fluid dynamics (CFD) simulations were performed over a range of wind speeds (4–10 m/s) and angles of attack to quantify the influence of strategically optimized VGs on airfoil aerodynamics. The results show that the streamwise vortices shed by the VGs transfer high-momentum fluid into the boundary layer, delaying separation and significantly reducing the adverse impact of separation bubbles. Consequently, the separated flow region is notably smaller, and the post-stall behavior is fundamentally altered: the abrupt stall of the clean airfoil is replaced by a gradual decline in performance. Although a modest drag penalty is observed before stall, the overall aerodynamic benefit is substantial. In the post-stall regime, the VG-equipped airfoil retains up to 30% higher lift and experiences considerably lower drag, leading to a pronounced improvement in the lift-to-drag ratio and an effectively widened operational envelope. This enhancement is most prominent at lower wind speeds, resulting in sustained rotor torque, improved operational stability, and a direct increase in annual energy production (AEP). The findings confirm that backward-facing aero-shaped vortex generators are a highly effective technology for optimizing HAWT performance.

Keywords: Horizontal Axis Wind Turbines (HAWT), Passive Flow Control, Vortex Generators (VGs), Computational Fluid Dynamics (CFD), Boundary Layer Separation, Separation Bubbles, Aerodynamic Optimization.

1 Introduction

Wind energy is a key renewable resource, reducing dependence on fossil fuels and mitigating climate change. Its clean and sustainable nature has driven rapid expansion through technological advancements. Horizontal-axis wind turbines (HAWTs) dominate the market due to their high efficiency, scalability, and reliability, converting the kinetic energy of wind into electricity via rotating blades. Their aerodynamic performance and adaptability make them the preferred choice for both onshore and offshore applications.

HAWTs nevertheless face significant challenges in maintaining optimal aerodynamic efficiency under variable wind conditions. Research efforts focus on blade aerodynamics and turbulence management, with vortex generators (VGs) (Fig. 1) emerging as an effective solution to delay flow separation and improve performance [1]. During stall, increased drag and reduced lift severely degrade rotor performance [2,3]. Flow control approaches address these challenges through either active or passive techniques [4–9]. Passive methods, particularly VGs, are favored for HAWTs because of their effectiveness and low cost [10–14]; they enhance momentum transfer into the near-wall region, thereby inhibiting flow detachment [12,15,16].

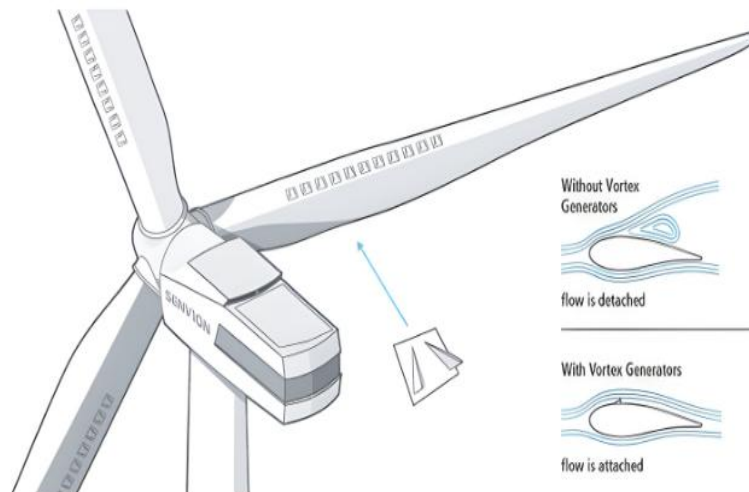


Fig. 1. VGs mounted on wind turbine blades [2].

Vortex generators significantly reduce vibrations, noise, and fatigue loads on wind turbine blades caused by stall, which has prompted considerable research into optimizing their aerodynamic performance and energy efficiency [12,17]. Originally developed by Taylor in 1947 for aircraft wings [18], VGs delay stall by increasing lift and minimizing drag [2,19]. Unlike aircraft wings, which may experience supersonic flow separation ($Ma > 1$), wind turbine blades operate in incompressible flow regimes ($Ma < 0.3$) [8,20]. On turbine blades, flow separation progresses from the trailing edge toward the leading edge, reducing lift and increasing drag [20,21].

Up-Wind Solutions, Inc. demonstrated that VGs can increase annual energy production (AEP) by 2.1–2.5 % [22–24], although effectiveness depends on wind speed, highlighting the need for configuration optimization. VGs generate longitudinal vortices (Fig. 2) that merge high-energy external flow with the low-energy boundary layer, thereby delaying separation [25]. These leading-edge vortices re-energize the boundary layer, as analyzed using particle image velocimetry (PIV) [26].

A laminar boundary layer produces lower skin friction but is more susceptible to separation, whereas a turbulent boundary layer withstands a greater adverse pressure gradient and delays separation. Vortex generators enhance turbulence downstream, promoting an earlier transition to a turbulent boundary layer a process crucial for stall delay and separation reduction [27]. Fig. 3 demonstrates the effect of counter-rotating (CtR) triangular VGs on an airfoil at $Re = 3 \times 10^6$, showing a significant increase in the static stall angle of attack and a 25 % improvement in the maximum lift coefficient (CL). VGs offer several advantages, including compact size, low cost, and ease of implementation [2]. Their small profile permits wide distribution along the blade and convenient replacement [28]. However, VGs introduce parasitic drag before the onset of flow separation [29].

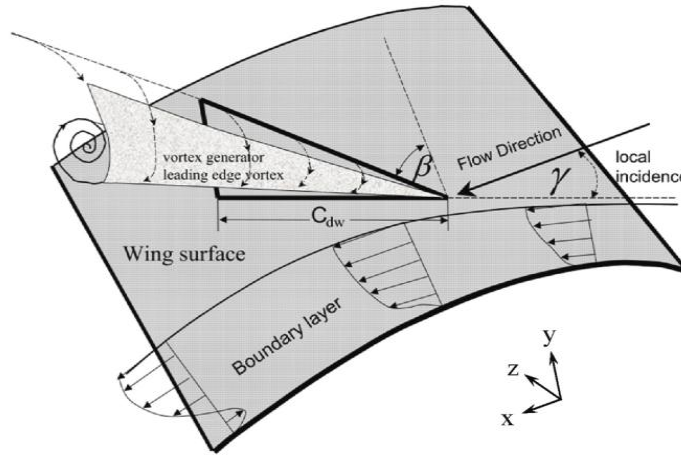


Fig. 2. Pressure distribution around an airfoil [36].

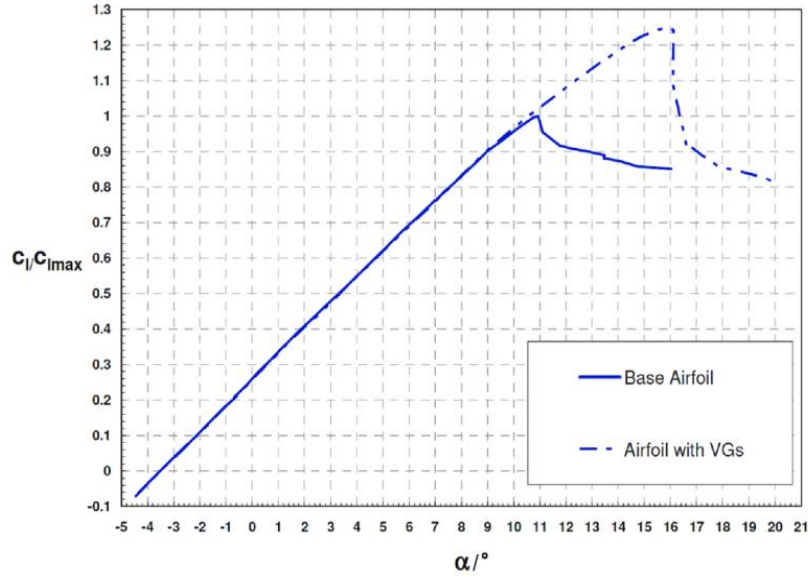


Fig. 3: Effect of VGs on airfoil lift [36].

The pursuit of enhanced aerodynamic efficiency in HAWTs remains a critical focus within wind energy research. A prominent passive flow control technique is the use of vortex generators. These small, strategically placed devices energize the boundary layer by introducing streamwise vortices, thereby delaying flow separation, increasing lift, and improving overall rotor performance, particularly under stalled conditions [14,30].

Recent studies have extensively explored the optimization of VG parameters. Investigations into VG height demonstrate its crucial role in boundary layer regulation, with optimal performance often linked to a height ratio (H/δ) near the boundary layer thickness [30]. The shape and arrangement are equally significant; computational studies have shown that chordwise length, spacing, and setting angle (β) directly influence vortex strength and core stability, with an optimal β typically between 10° and 30° [31–33]. Moreover, the radial location of VG installation on a blade is not arbitrary; optimal placement is essential to maximize AEP gains and avoid performance degradation from improper retrofitting [34,35]. Novel designs, such as aero-shaped VGs, promise improved performance over conventional triangular VGs by offering a superior aerodynamic profile [14]. Research has also examined specialized configurations such as counter-rotating and co-rotating arrays, whose effectiveness can be influenced by external factors including wind direction and blade tip deflection [30].

A compelling avenue for performance enhancement lies in combining multiple passive flow control techniques. For instance, integrating slots with VGs has been identified as a promising yet underexplored method for controlling boundary layer transition and separation [36]. Independently, slotted airfoils have demonstrated notable improvements in aerodynamic efficiency and aeroacoustic performance at high angles of attack [14], suggesting synergistic potential when combined with VGs.

These diverse studies are summarized in Table 1, which categorizes findings based on VG types and arrangements. Although the existing body of work provides a robust foundation with the triangular type being the most common, significant research gaps remain. The interaction between hybrid flow control systems (e.g., slots and VGs) and their combined effect on full-scale HAWT rotor performance under realistic operating conditions requires further detailed investigation. Much of the current understanding derives from isolated airfoil studies or simplified models, necessitating advanced, coupled computational fluid dynamics (CFD) and computational structural dynamics (CSD) methods to accurately capture fluid–structure interaction effects on a rotating blade [30].

Therefore, this paper aims to address this gap by systematically evaluating the impact of vortex generators, both independently and in conjunction with other passive flow control techniques, on the aerodynamic and structural performance of a modern HAWT blade. Utilizing high-fidelity numerical simulations, this study will quantify improvements in power coefficient, analyze the suppression of flow separation, and assess the structural loads induced by the implemented devices.

Table 1. A Researches comparison of VGs impact on wind turbines [31].

Investigators (Year, Pub.)	Case Profiles	VGs Types	ΔC_L (%)	L/D (%)	α_{Stall}	Comments
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Li, et al, 2019 [30]	DU93-W-210 airfoil had (C=0.305 m & S=0.071 m)	Triangle VGs at different height	48.6	564-880 at ($\alpha = 20^\circ$)	10°	The increasing of attack angle improves the lift-to-drag ratio of the airfoil with VGs
Li, et al., 2019 [31]	DU93-W-210 airfoil had (C=0.305 m & S=0.071 m)	Triangle VGs at different Installation angles	48.8	-	-	The best improvement of lift-to-drag (L/D) ratio at ($\beta = 20^\circ$)
Algan, et al., 2023 [38]	NACA 4415 airfoil had (C=148.5 mm & S=297 mm)	Triangle VGs	18.8	9.53	4°	Aero-shaped VGs enhanced lift-to-drag (L/D) ratio compared to the baseline and conventional CVGs
		Aero-Shaped VGs	12.8	18.5	4°	
Jiang, et al., 2023 [39]	NREL Phase VI turbine has a rotating radius(R) of 5.029 m, S809 airfoil	Triangle CtR and CoR VGs at different height	-	-	-	1. The CtR VGs increased torque by 10.82% at ($z = 2h$ & $U=10$ m/s) 2. The CoR VGs increased torque by 17.88% at ($z = 3h$ & $U=10$ m/s)
Nia B B, et al., 2023 [40]	DU-97-W-300	Rectangular VGs	-	112	-	1. CVG provides higher lift, but more drag at pre-stall angles 2. Slot exit jet performs well in post-stall angles
		Slot Airfoil	-	91	-	
Lee H M, et al, 2019 [32]	NACA 64-618 airfoil with a rotor	Rectangular VGs	-	-	-	Increase the normal and tangential

	radius of 63 m					forces, leading to more efficient energy capture, which increase 1.04% at output power and Strong vortices generated, contributing to delayed flow separation
Moon, et al, 2019 [33]	DU airfoil with rotor diameter of 113 m	Triangle VGs	-	-	-	Increases, especially above 5.9° angle of attack Decreases, especially at angles of attack beyond 14.8°
Akhter M Z, et al, 2024 [36]	S809 airfoil had (C=0.305 m & S=0.071 m)	Slot Airfoil	130 at ($\alpha = 17^\circ$)	372 at ($\alpha = 20^\circ$)	1°	Significant improvement lift-to-drag (L/D) ratio at higher angles
Skrzypiński W, et al., 2019 [34]	NACA 63-4XX airfoils (2D)	Triangle VGs at different Locations	-	-	-	The increase in annual energy production (AEP) of 2.7% to 2.9%
Li X K, et al., 2014 [31]	DTU 10 MW	Triangle VGs at different Locations	44 to 65	-	-	The increase in annual energy production (AEP) of 3.6% to 10.1%

2 Computational Methodology and Validation

2.1 Turbine Model and Computational Domain

The subject of this study is a horizontal-axis wind turbine with a rotor diameter of 4 m. The rotor assembly consists of an aluminum hub and three composite blades fabricated from fiberglass. Each blade has a span of 1.75 m and is attached to the hub using aluminum male pins. The airfoil profile along the blade span follows the NACA 4418 design, selected for its favorable aerodynamic characteristics that aim to maximize the lift-to-drag ratio under the specific operating conditions and Reynolds number of this application [19].

A computational model of the wind turbine was developed in SolidWorks for numerical simulation. The blade geometry is shown in Fig. 4. To accurately model the external flow field, a finite computational domain was constructed. The domain size is critical; it must be sufficiently extensive to ensure that the prescribed boundary conditions do not artificially influence the flow phenomena around the rotor and faithfully represent free-stream conditions [18].

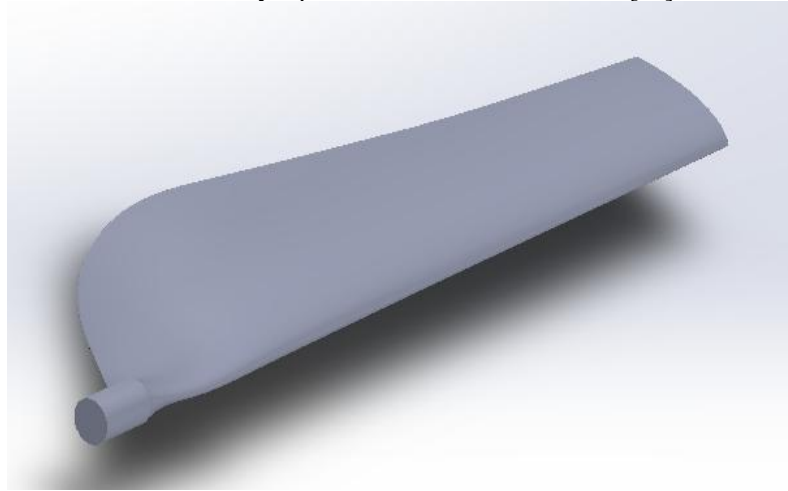


Fig. 4: Blade of the wind turbine rotor.

To simulate the rotational motion, a cylindrical rotating domain encapsulating the turbine blades was created. The complete three-dimensional computational model is illustrated in Fig. 5. The rotating domain is a 120° sector, exploiting the three-bladed rotor's periodicity to reduce computational cost. The stationary domain represents the ambient wind field. A General Grid Interface (GGI) connects these regions.

A polyhedral mesh with prismatic boundary layers was employed, resolving the near-blade flow with a y^+ value below 1 for the $k-\omega$ SST turbulence model. Boundary conditions included a uniform velocity inlet, a pressure outlet, and periodic interfaces for the sector faces. Simulations were run to steady-state convergence to evaluate performance coefficients for optimization.

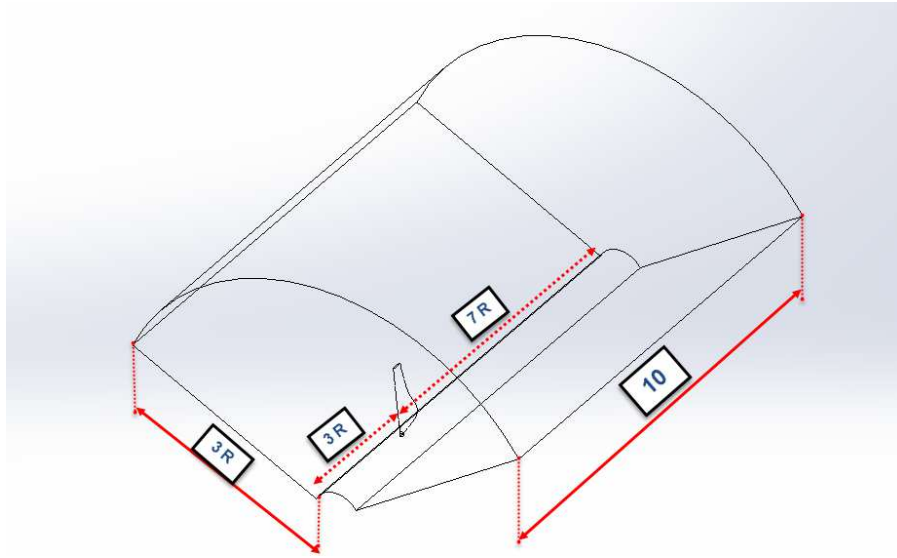


Fig. 5: Sector modeling the area near rotor created using SolidWorks Program.

2.2 Mesh Generation

The accurate computational resolution of aerodynamic forces such as lift and drag is critically dependent on mesh quality. A high-resolution grid is required in the immediate vicinity of the blade to capture steep flow gradients and boundary layer phenomena, while a coarser outer domain adequately models far-field conditions. A uniformly dense mesh across the entire domain is computationally prohibitive. To achieve an optimal balance between accuracy and efficiency, a multi-tiered meshing strategy was employed. This approach uses a high-density fine mesh surrounding the airfoil surfaces, which transitions progressively to a coarser mesh in the far-field region [18], as illustrated in Fig. 6.

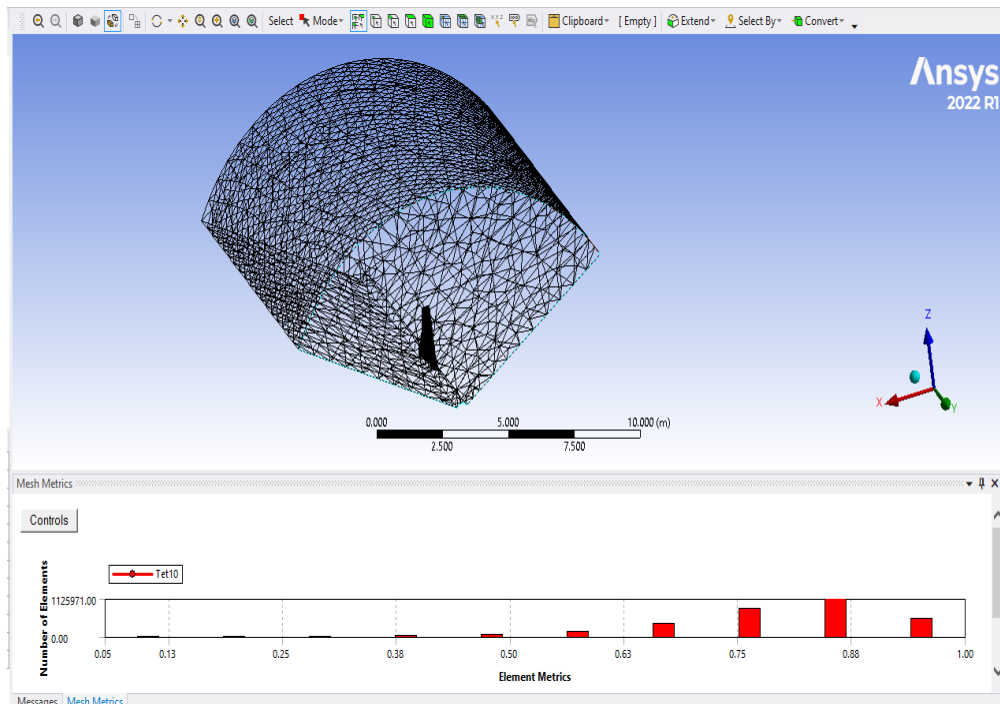


Fig. 6: ANSYS CFX Mesh Strategy.

Specific refinement ensured sufficient resolution of the boundary layer using prismatic inflation layers near the wall, characterized by a first-layer thickness calculated to achieve a target y^+ value appropriate for the selected turbulence model. The mesh density was also strategically enhanced in regions of expected high flow curvature, such as the leading and trailing edges. The resulting structure, shown in Fig. 7, demonstrates the high resolution around the turbine blades and the gradual coarsening toward the domain boundaries.

All numerical simulations were performed using the ANSYS CFX solver on a system equipped with an Intel Core i7 processor and 32 GB of RAM. The convergence criterion for all simulations was a reduction of all scaled residuals below 10^{-4} .

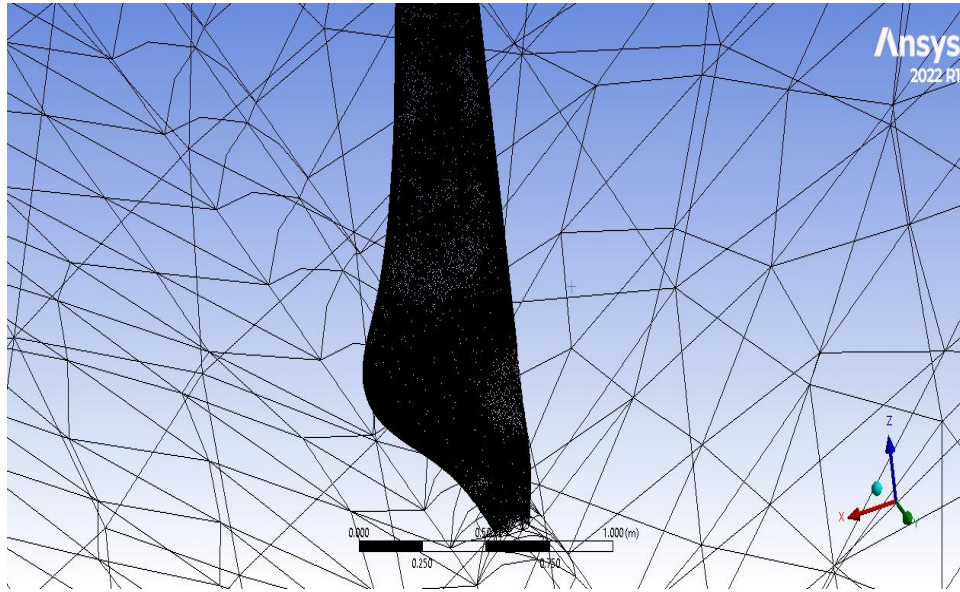


Fig. 7: Mesh detailing blade proximity sizing and inflation layers.

2.3 Governing Equations and Mesh Validation

The fundamental governing equations for fluid flow derive from the conservation laws of mass, momentum, and energy. These principles are expressed as a set of partial differential equations formulated under the continuum mechanics assumption. Within the Finite Volume Method (FVM) framework used in this study, the physical domain is discretized into a finite set of control volumes. The partial differential equations are integrated over each control volume, transforming them into a system of algebraic equations that are solved iteratively for flow variables such as velocity, pressure, and density. This methodology forms the core of CFD [37].

A grid convergence study (GCI) was conducted to ensure that the numerical results were independent of the mesh density, as shown in Fig. 8. The aerodynamic performance, quantified by the power output, was calculated for several meshes of varying resolution. The mesh consisting of approximately 6.5 million cells was identified as providing a mesh-independent solution. This mesh also yielded the best agreement with the experimental power curve, giving results within a 5–10 % error margin relative to the reference data (Fig. 9) and was therefore adopted for all subsequent simulations.

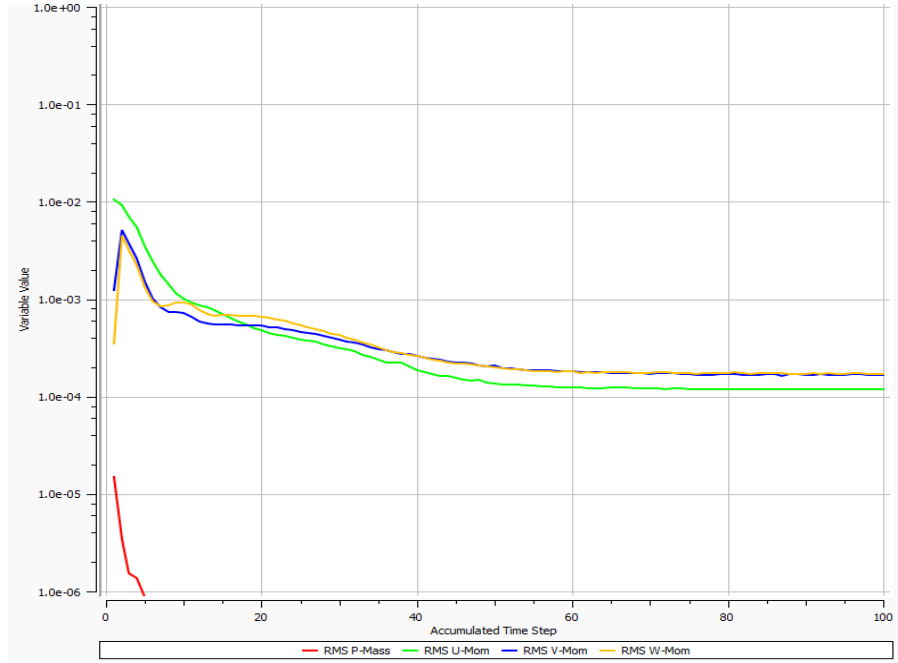


Fig. 8: Grid convergence study results.

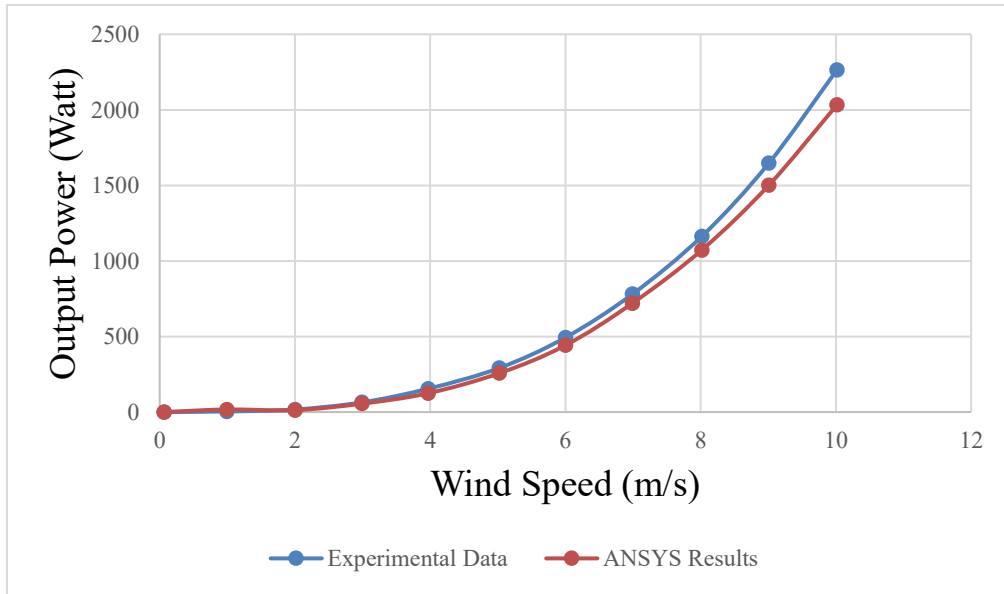


Fig. 9: Experimental and Computational Wind Turbine Power.

2.4 Baseline Flow Separation and Vortex Formation

Simulations of the baseline HAWT blade configuration consistently predict extensive flow separation initiating at the trailing edge of the suction surface. As visualized in Figs. 10 and 11 for representative wind velocities (4 m/s and 10 m/s), this separation evolves into a dominant recirculation bubble. The primary driver is a steep adverse pressure gradient, which prompts boundary layer transition and subsequent detachment from the airfoil surface.

Downstream of the separation point, the emergent shear layer becomes unstable. The growth of Kelvin–Helmholtz instabilities within this layer causes it to roll up into a series of discrete, counter-rotating vortices. These coherent structures are

self-sustaining and establish a sizable zone of recirculating flow characterized by high turbulence and a pronounced momentum deficit. Aerodynamically, this manifests as premature stall onset, a sharp decline in lift, and a dominant rise in pressure drag, collectively degrading overall blade performance. Observing this flow topology directly substantiates the use of vortex generators for flow control. The core rationale is to introduce targeted momentum into the boundary layer to counteract the adverse pressure gradient, thereby mitigating separation and promoting flow reattachment.

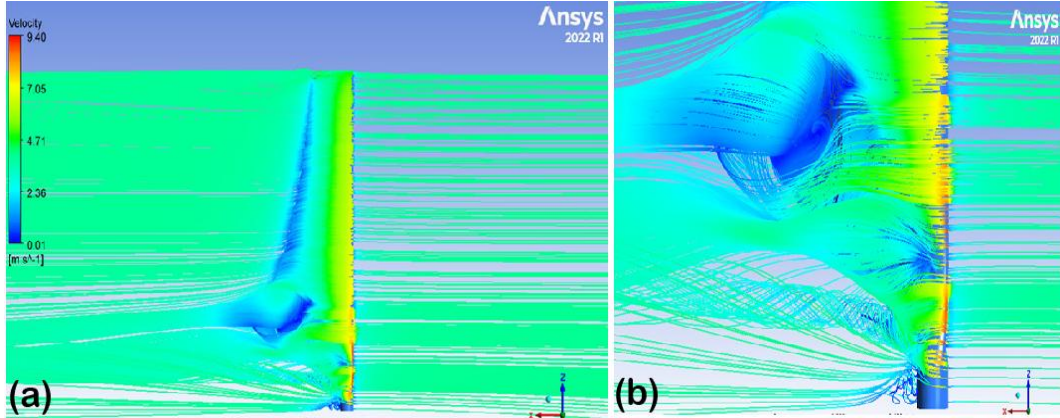


Fig. 10: (a) Streamlines over the blade suction surface at 4 m/s, (b) zooming at separation bubble.

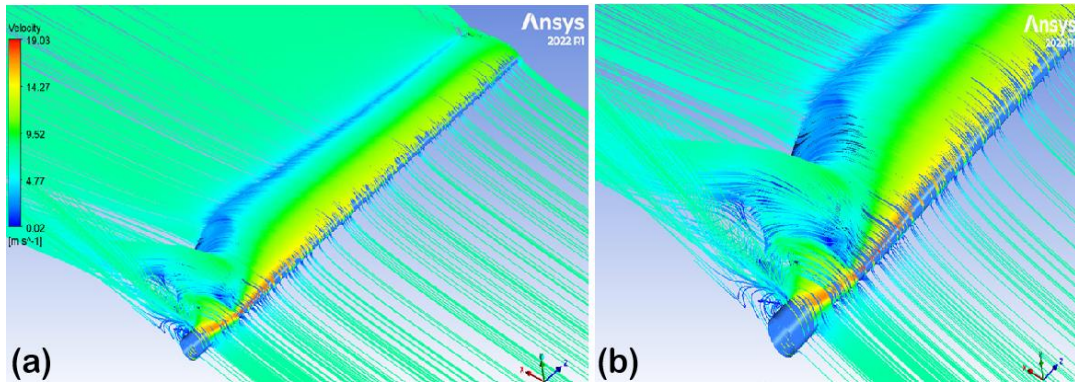


Fig. 11: (a) Streamlines over the blade suction surface at 4 m/s, (b) zooming at separation bubble.

3 Aero-Shaped Vortex Generator Configuration and Performance

3.1 VG Geometry and Parametric Optimization

This study examines aerodynamically shaped vortex generators deployed in a co-counter rotating arrangement. The geometric parameters of the VGs were defined following established methodologies [12]; a comprehensive summary of these dimensions is provided in Table 2. The orientation and placement of the VGs on the NACA 4418 airfoil are schematically detailed in Fig. 12. Given the extensive parameter space, a structured parametric study was undertaken. The initial phase focused on evaluating traditional rectangular VG configurations to establish a performance baseline and identify an optimal set of parameters (e.g., height, spacing, chordwise position).

Table 2. Parameters of Aero-shaped VGs.

Parameters	Aero-shaped VGs
Height (mm)	10 – 20 mm

Chord (mm)	15 mm
Spacing (mm)	50 mm
Setting angle β (°)	- 20 – 40
x/c (% c)	0.1 - 0.4

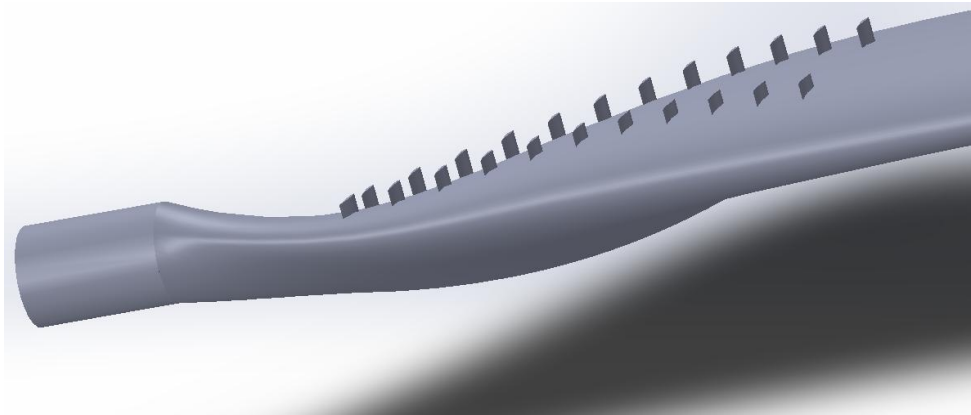


Fig. 12: NACA 4418 with vortex generator (Backward-Facing).

To specifically attribute aerodynamic effects to profile geometry, the parametric configuration optimized for conventional VGs was directly transposed to the aero-shaped designs. This controlled approach was fundamental, as it isolated the variable of cross-sectional shape, allowing its distinct influence on vortex formation and downstream flow structure to be delineated.

In parallel, candidate thin-airfoil profiles were assessed to identify an optimal section for the VGs themselves. Selection criteria prioritized profiles with documented aerodynamic advantages, particularly in maintaining stable vortex generation and minimizing inherent drag. The comparative aerodynamic performance of these candidate sections is summarized in Table 3, with their relative efficacy quantified by the lift-to-drag ratios presented in Fig. 13.

Table 3. Best Aero-Shaped for smoothing flow.

Airfoil	Max C_L/C_D	Key Features
NACA 0006	Moderate	Low drag, good for laminar flow
NACA 0012	High	Stronger vortices, best lift-to-drag improvement
Selig 1223	Best	Excellent lift-to-drag, used in high-performance applications

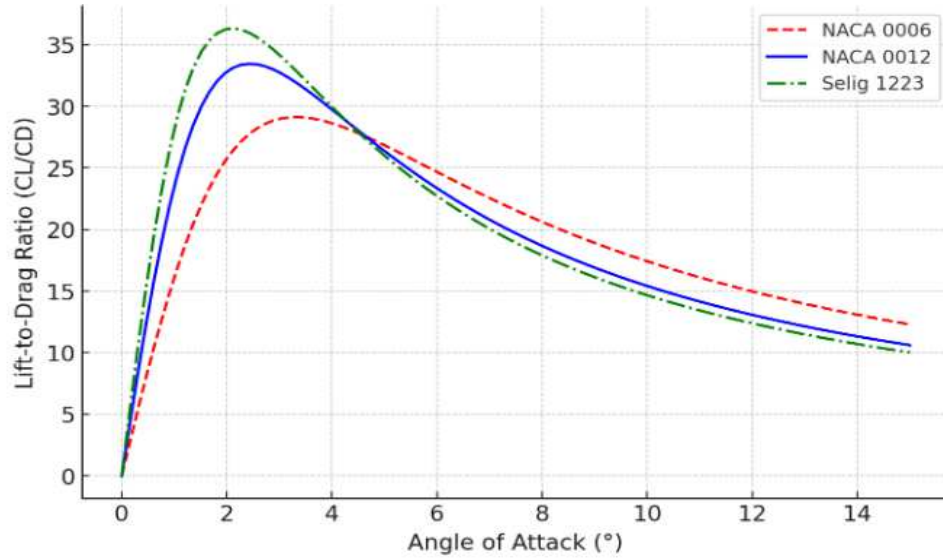


Fig. 13: Comparison of Different Thin Airfoils VGs.

3.2 Effect of VGs on Flow Separation Bubble

The efficacy of vortex generators in moderating flow separation was evaluated by examining the aerodynamic performance of an HAWT blade across operational angles of attack and free-stream velocities of 4, 6, 8, and 10 m/s. Separation fundamentally undermines turbine efficiency by causing a decline in the lift coefficient (C_L) and an attendant rise in the drag coefficient (C_D). To quantify this effect and the subsequent mitigation by VGs, CFD simulations mapped the separation topology and extracted corresponding force coefficients for each simulated condition.

Streamline patterns over the blade surface, depicted in Figs. 14 and 15, demonstrate the role of VGs in boundary layer management. The flow remains attached over a significantly greater portion of the suction surface compared to the baseline case. This visual evidence confirms a delayed separation onset and a material contraction of the recirculation region.

This performance gain originates from the system of streamwise vortices shed by the VGs. These organized structures act as conduits, transporting momentum from the inviscid outer flow into the near-wall region. This supplemental energy increases the boundary layer's resistance to the local adverse pressure gradient, thereby curtailing its separation tendency. The direct aerodynamic consequence is an improved lift-to-drag ratio across the post-stall regime. For the rotating turbine, this translates to more sustained torque generation and enhanced overall energy capture efficiency.

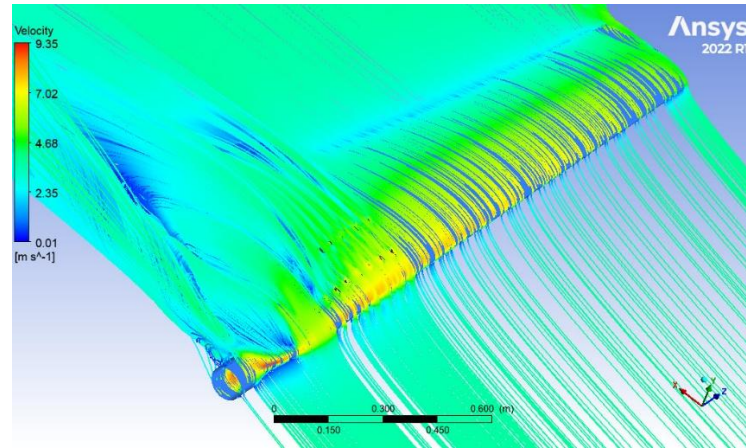


Fig. 14: Streamlines over the blade suction surface at $U = 4 \text{ m/s}$.

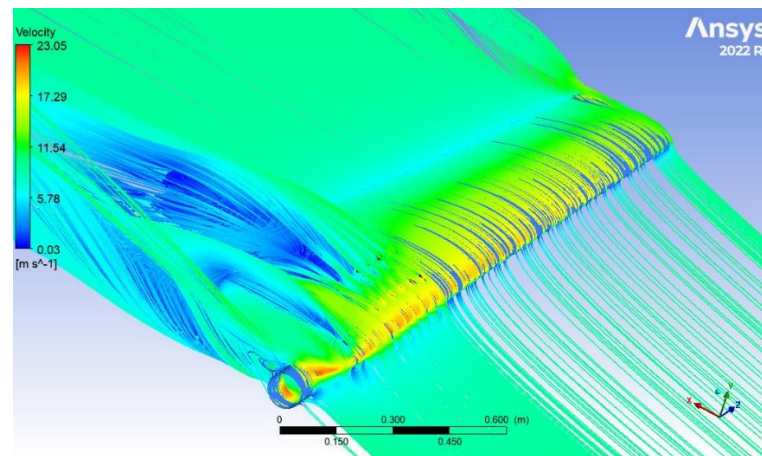


Fig. 15: Streamlines over the blade suction surface at $U = 10 \text{ m/s}$.

Analysis of the flow field reveals smooth, curved streamlines that conform to the blade contour, indicating predominantly attached flow across both the suction and pressure surfaces. Attached flow is a key indicator of efficient aerodynamic performance. Potential regions of flow separation are observed near the trailing edge, as illustrated in Figs. 16 and 17. The presence of vortex generators appears to mitigate the extent of this separation by energizing the boundary layer, although some localized effects remain.

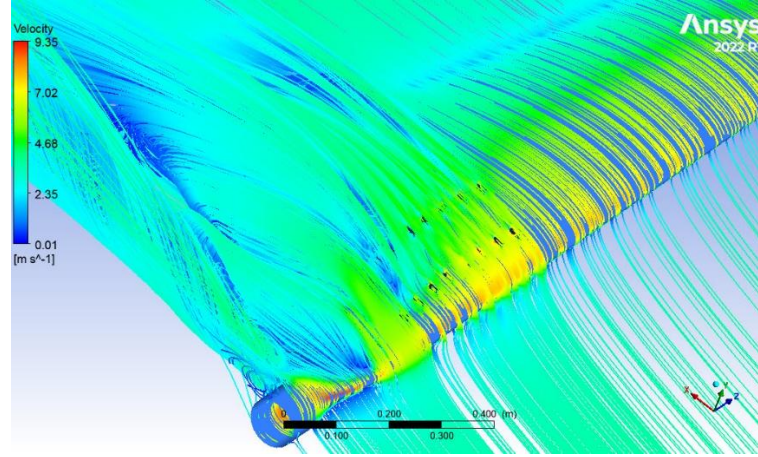


Fig. 16. Improvement Flow separation over the blade.

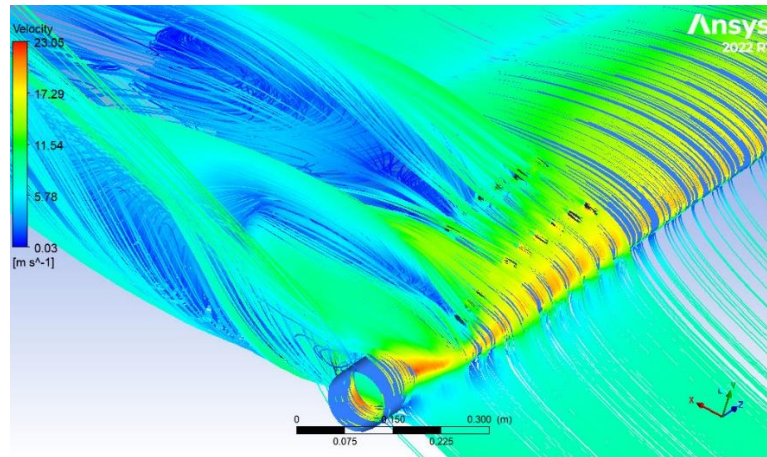


Fig. 17. Improvement Flow separation over the blade.

3.3 Aerodynamic Performance Enhancement

For effective implementation, thin-airfoil vortex generators are positioned on the outboard sections of HAWT blades, targeting regions where pronounced adverse pressure gradients typically initiate boundary layer separation. Their final geometric configuration encompassing chordwise location, spanwise spacing, and setting angle (β) was derived from an extensive CFD-driven parametric optimization. This rigorous process refined the geometry to maximize the generation of stable streamwise vortices, which augment momentum within the boundary layer and thus postpone flow detachment.

The aerodynamic consequence is a definitive enhancement in sectional performance. The modified airfoil exhibits a higher lift coefficient, a suppressed post-stall drag rise, and a consequently improved lift-to-drag ratio across a broad range of angles of attack. Translating this to full rotor performance, the augmentation of the power coefficient (C_p) extends operation to lower effective cut-in wind speeds and elevates annual energy yield. These gains collectively improve the turbine's efficiency and bolster the economic viability of the installation.

Lift Enhancement

Using thin airfoils as VGs increases effective lift coefficient (C_L) by re-energizing the boundary layer as shown in Figures (17 – 20) for wind Speeds 4, 6, 8 and 10 m/s:

$$C_{L.VG} = C_{L.o} \times \Delta C_L$$

where:

$C_{L.VG}$ = Lift coefficient with VGs

$C_{L.o}$ = Lift coefficient without VGs

ΔC_L = Incremental lift due to vortex enhancement

The influence of vortex generators on airfoil performance is strategically selective. At pre-stall angles of attack ($\text{AoA} < 10^\circ$), where the flow remains fully attached, their presence induces a negligible perturbation to CL. This indicates that VGs successfully preserve the baseline aerodynamic efficiency of the blade under standard operational conditions. Their principal utility, however, is realized beyond the critical stall angle (approximately 10° – 15°). In this regime, VGs fundamentally modify the stall characteristic: the sharp, abrupt loss of lift typical of the baseline blade is effectively mitigated, transforming into a more gradual and controlled decline in performance. This moderated stall behavior enables significantly augmented lift retention, with CL values over 30 % higher than the baseline at post-stall angles up to 25° , as quantified in Figs. 18 and 19.

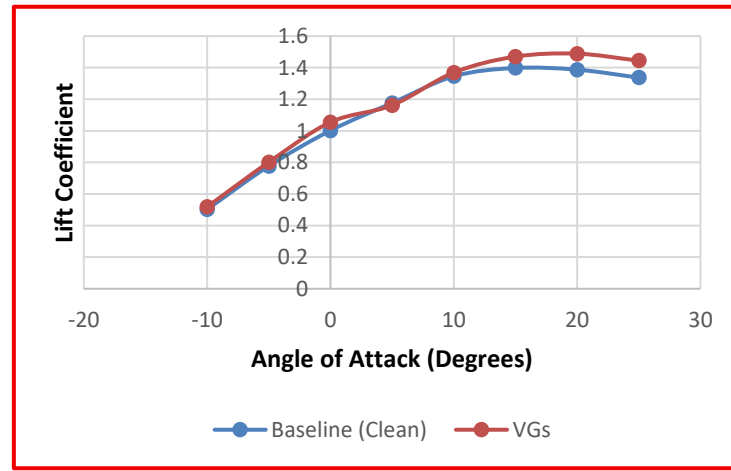


Fig. 18. The effect of VGs on Lift Coefficient at $U = 4$ m/s.

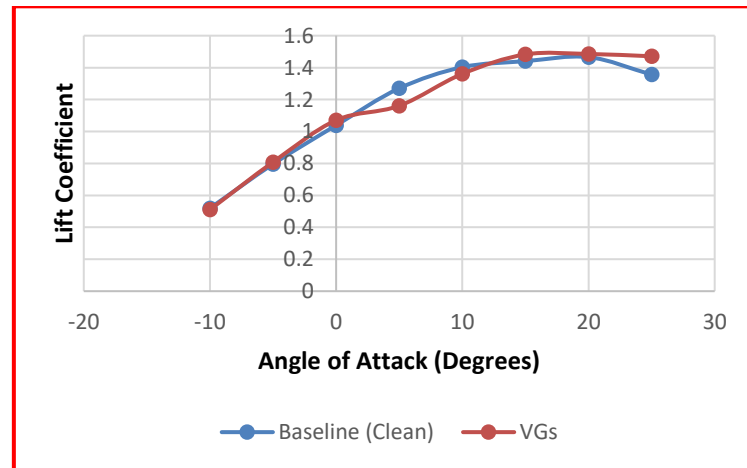


Fig. 19. The effect of VGs on Lift Coefficient at $U = 6$ m/s.

This enhancement mechanism proves consistent across the simulated wind spectrum of 4–10 m/s, corresponding to a range of Reynolds numbers. The benefit, however, displays a clear dependency on flow speed. It is most pronounced at the lower velocities of 4–6 m/s, where naturally thicker boundary layers exhibit a greater propensity for separation, thereby offering greater potential for VG intervention.

While persistent, the relative enhancement in CL at elevated wind speeds diminishes slightly, as evidenced in Figs. 20 and 21. This attenuation can be ascribed to the thinner, more momentum-rich boundary layers prevalent at higher Reynolds numbers, which are inherently more resistant to modification. The core working mechanism, however, remains unchanged: the VGs shed coherent streamwise vortices that actively entrain high-energy freestream fluid, reinvigorating the near-wall flow and fortifying it against the adverse pressure gradient.

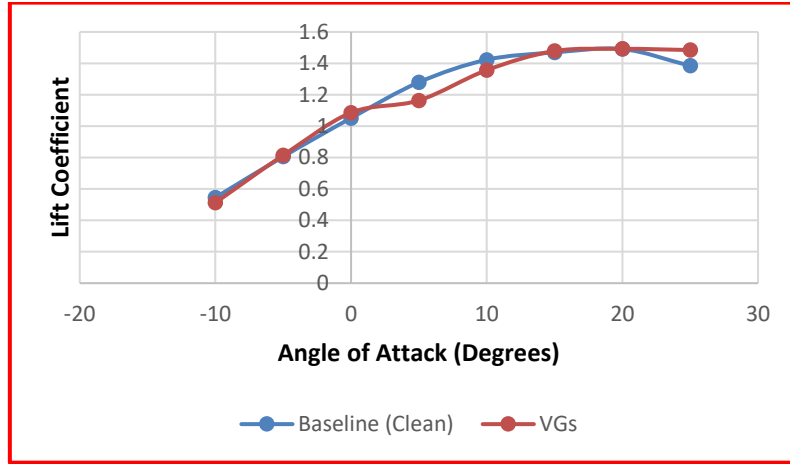


Fig. 20. The effect of VGs on Lift Coefficient at $U = 8$ m/s.

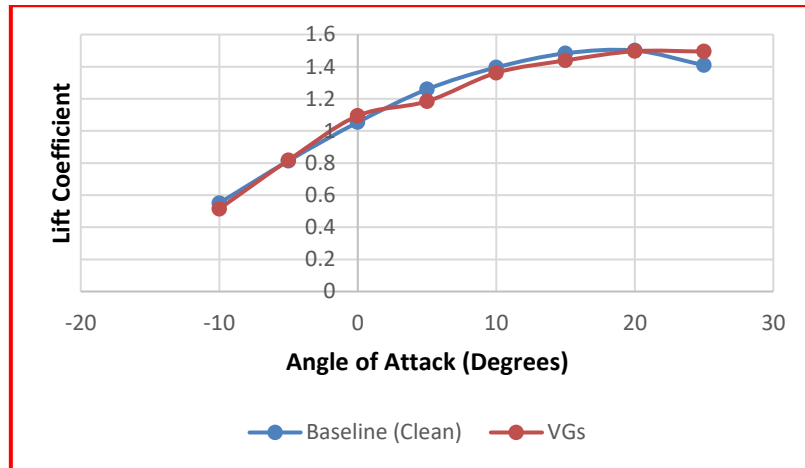


Fig. 21. The effect of VGs on Lift Coefficient at $U = 10$ m/s.

Ultimately, the principal aerodynamic contribution of VGs lies not in elevating the maximum lift coefficient, but in substantially broadening the blade's functional operating range. The devices defer stall onset by roughly 5° and maintain effective performance at subsequently higher angles of attack, effectively extending the viable AoA range by 20–25 %. This expansion of the stable operating regime sustains higher rotor torque and boosts annual energy production (AEP). These benefits are especially valuable at low wind speeds, where preventing stall is paramount for maintaining energy capture.

Reduction in Drag

By delaying separation, VGs reduce separation drag (C_D), as shown in Figures (21 – 24) for wind Speeds 4, 6, 8 and 10 m/s:

$$C_{D,VG} = C_{D,o} \times \Delta C_D$$

where:

$C_{D,VG}$ = Drag coefficient with VGs

$C_{D,o}$ = Drag coefficient without VGs

ΔC_D = Represents the reduction in drag due to improved boundary layer characteristics.

Drag coefficient analysis across the operational wind speed spectrum reveals a consistent aerodynamic compromise introduced by vortex generators. A modest but measurable increase in C_D is observed in the pre-stall regime ($AoA < \sim 15^\circ$),

evident as a slight upward shift in the data series across all corresponding figures. This penalty is the direct consequence of parasitic pressure drag imposed by the physical profile of the VGs themselves.

The principal benefit, however, emerges decisively post-stall. The baseline blade exhibits a characteristically sharp, exponential rise in C_D beyond $\sim 15^\circ$ AoA—the signature of massive, uncontrolled flow separation. As Figs. 22–25 demonstrate, the VG-equipped configuration fundamentally disrupts this trend, achieving pronounced mitigation of the stall-induced drag divergence. The governing mechanism is the re-energization of the boundary layer by VG-generated streamwise vortices, which contain the separation zone and suppress the associated surge in pressure drag. Quantitatively, this translates to C_D values at high angles of attack (20° – 30°) that are substantially lower than the baseline.

The magnitude of this drag-reduction benefit is inversely related to wind speed. It is most significant at lower velocities (4–6 m/s), as captured in Figs. 22 and 23, where the VGs prove highly effective at curtailing the formation of the post-stall drag peak.

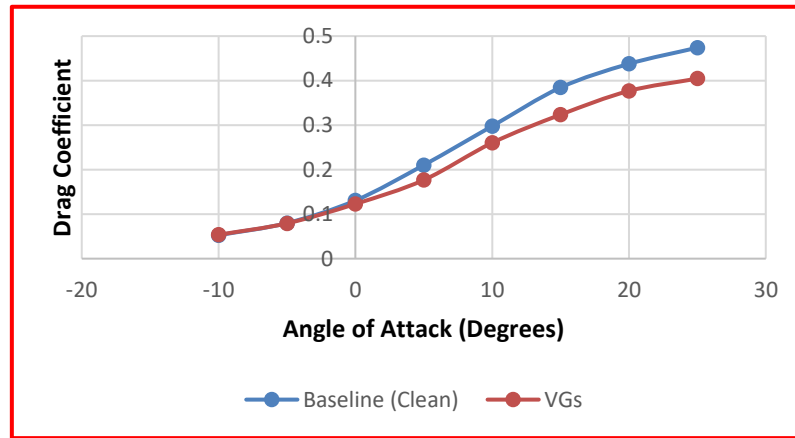


Fig. 22. The effect of VGs on Drag Coefficient at $U = 4$ m/s.

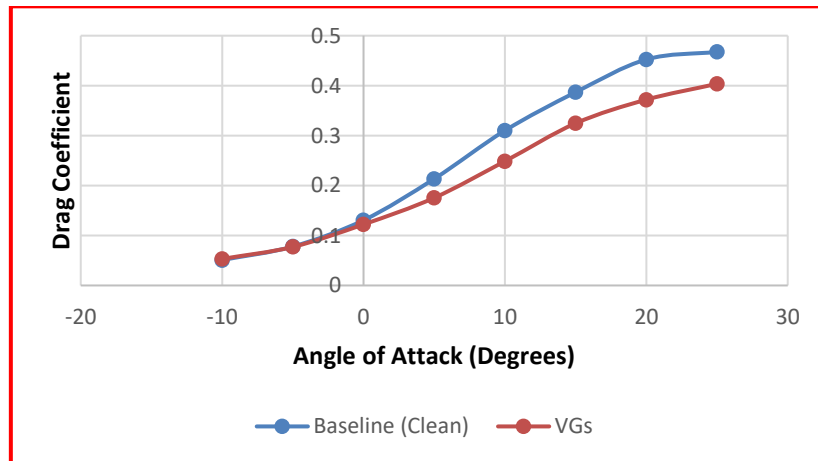


Fig. 23. The effect of VGs on Drag Coefficient at $U = 6$ m/s.

At higher wind speeds (8–10 m/s), the relative drag-reduction benefit, while still evident (Figs. 24 and 25), is attenuated. This is attributed to the naturally thinner and more momentum-rich boundary layers at elevated Reynolds numbers, which are inherently less prone to separation, thereby reducing the scope for VG intervention. The net aerodynamic outcome across the operational envelope is a significantly enhanced lift-to-drag ratio within the post-stall regime. This improvement directly supports maintained rotor torque production under low-wind conditions, attenuates load fluctuations to improve operational stability, and effectively widens the turbine's operational envelope—all contributing to a quantifiable increase in AEP.

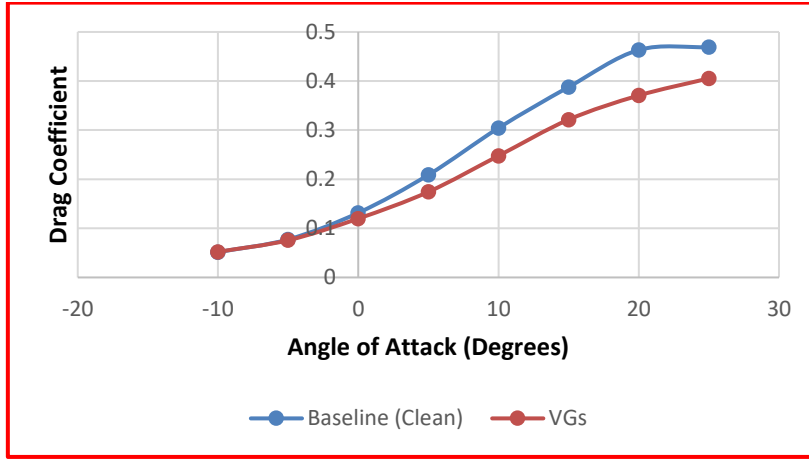


Fig. 24. The effect of VGs on Drag Coefficient at $U = 8$ m/s.

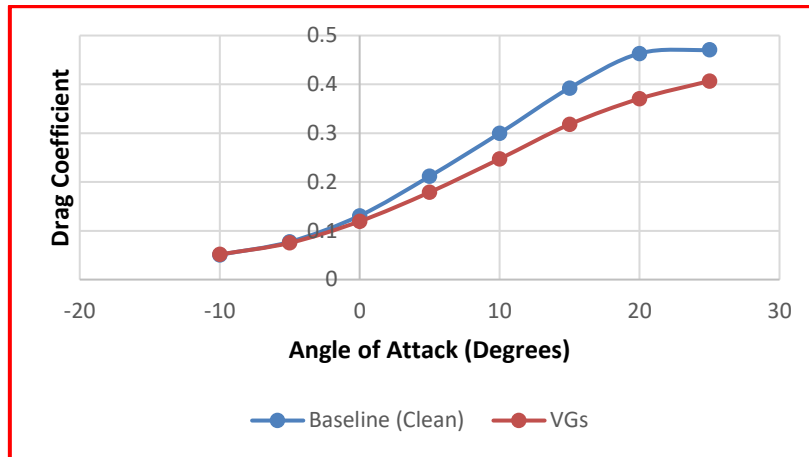


Fig. 25. The effect of VGs on Drag Coefficient at $U = 10$ m/s.

Enhancement of Lift-to-Drag Ratio

The integrated lift-to-drag (L/D) ratio, presented in Figs. 26–29, quantifies the net aerodynamic impact of the vortex generators, synthesizing their effects on both lift and drag. This analysis confirms that VGs produce a minor compromise in peak efficiency but confer a profound improvement in post-stall performance.

In the pre-stall regime ($AoA < \sim 15^\circ$), the VG-equipped blade shows a marginally reduced maximum L/D ratio relative to the clean baseline—a direct attribution to the parasitic drag introduced by the devices. This result confirms that VGs do not enhance performance at the design point of optimal attached flow, where the baseline blade achieves a sharper, superior L/D peak.

The principal advantage emerges decisively post-stall ($AoA > \sim 15^\circ$). While the baseline configuration suffers a characteristic aerodynamic stall, defined by a sharp and severe collapse in L/D, the VGs fundamentally modify this behavior. As the figures illustrate, the L/D progression for the modified blade transitions from a “peak-and-crash” to a “peak-and-plateau” characteristic. The streamwise vortices sustain boundary layer energy, postponing large-scale separation and preserving attached flow over a greater chordwise extent. This yields two definitive improvements: first, L/D values at high angles of attack (20° – 30°) remain significantly elevated compared to the stalled baseline; second, the blade’s operational range is substantially broadened, maintaining useful aerodynamic efficiency well beyond the baseline stall angle.

Furthermore, this benefit demonstrates a distinct Reynolds number dependency. The enhancement is most pronounced at lower wind speeds of 4 and 6 m/s (Figs. 26 and 27), where VGs are exceptionally effective in preventing the complete post-stall degradation of aerodynamic efficiency.

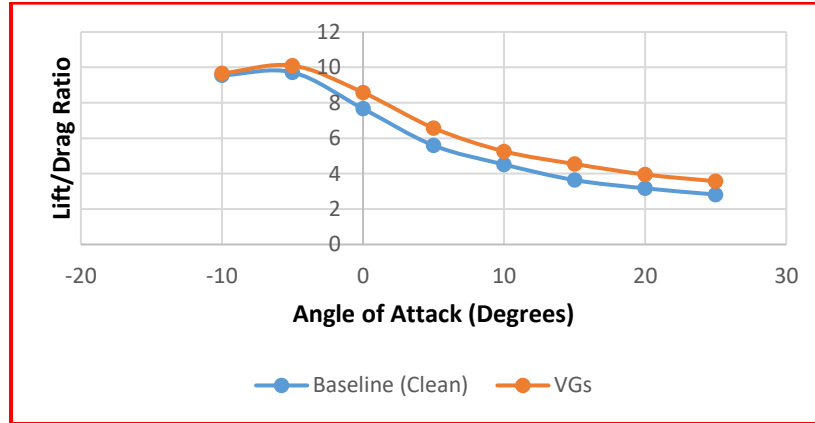


Fig. 26. The effect of VGs on L/D Ratio at $U = 4$ m/s.

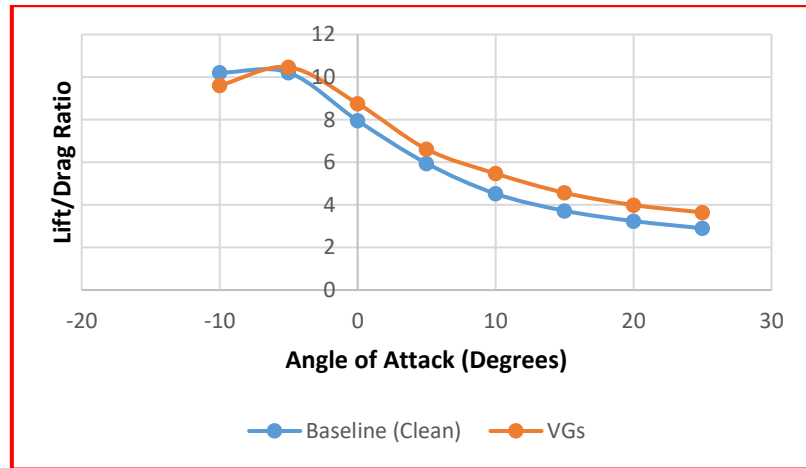


Fig. 27. The effect of VGs on L/D Ratio at $U = 6$ m/s.

While the absolute L/D values increase with wind speed for both configurations (Figs. 28 and 29), the relative improvement provided by the VGs in the post-stall region remains significant, though the stark contrast seen at lower speeds is somewhat moderated.

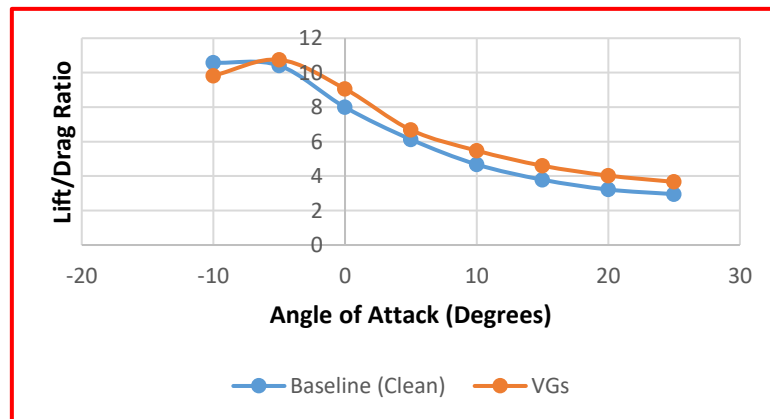


Fig. 28. The effect of VGs on L/D Ratio at $U = 8$ m/s.

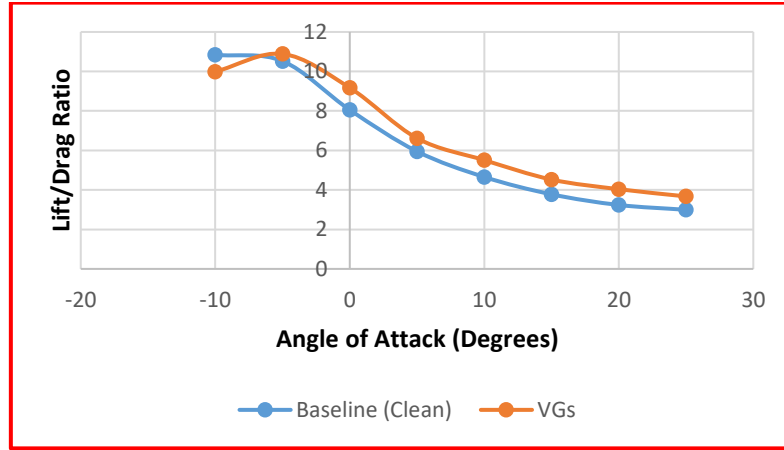


Fig. 29. The effect of VGs on L/D Ratio at $U = 10$ m/s.

4 Conclusions

This numerical investigation has evaluated the aerodynamic influence of backward-facing aero-shaped vortex generators on the performance of a horizontal-axis wind turbine blade, employing CFD simulations spanning wind speeds from 4 to 10 m/s. The results establish that the strategic application of VGs produces a net positive effect, primarily through a fundamental modification of the blade's stall characteristics.

The underlying flow mechanism is the generation of persistent streamwise vortices, which augment momentum within the boundary layer, re-energizing the near-wall flow and increasing its resilience against the adverse pressure gradient on the suction surface. Flow visualization corroborates this, showing a demonstrable delay in separation onset and a contraction of the recirculation zone relative to the baseline blade.

Quantitatively, this flow control manifests as three interconnected aerodynamic enhancements. First, the stall behavior is transformed: rather than increasing the peak lift, VGs convert the baseline's abrupt lift loss into a gradual, controlled decrease, preserving lift coefficients over 30 % higher at post-stall angles near 25°. Second, while incurring a minor pre-stall parasitic drag penalty, the VGs dramatically mitigate the exponential post-stall drag rise, yielding substantially lower drag coefficients at high angles of attack. Third, the synergistic result is a significantly improved lift-to-drag ratio in the post-stall regime; the characteristic performance “crash” is replaced by a stabilized “plateau,” extending the range of aerodynamically efficient operation.

The magnitude of these benefits displays a clear dependency on wind speed, being most substantial at lower velocities (4–6 m/s), where boundary layers are inherently more susceptible to separation. For HAWT operation, these improvements are consequential: they promote maintained torque production in low-wind conditions, enhance operational stability by smoothing transient loads, and effectively widen the operational envelope. Collectively, these factors contribute directly to increased annual energy production (AEP). The findings confirm that backward-facing aero-shaped vortex generators constitute an effective passive flow control technology for enhancing the aerodynamic performance and economic viability of wind turbine systems.

5 Future Directions

While this work substantiates the benefits of aero-shaped vortex generators, it also identifies key avenues for further research:

- **Full-Scale Rotor and Annual Energy Production Analysis:** Future studies should progress to high-fidelity CFD simulations of a complete 3D rotor, integrated with aero-elastic and system-level models, to accurately predict the net effect on the turbine power curve and the resulting increase in AEP under realistic, turbulent inflow.
- **Optimization for Extended Operating Conditions:** The current parametric study considered a specific operational range. Subsequent work could investigate VG configurations optimized for a wider spectrum of Reynolds numbers and yaw conditions to maximize annual performance. This may involve designing radially varying or aerodynamically adaptive geometries for different blade segments.

- **Comparative Assessment with Alternative Flow Control Technologies:** A formal techno-economic comparison between VGs and other passive devices (e.g., Gurney flaps, serrated trailing edges) or active flow control systems would offer valuable guidance for industry. Evaluating the trade-off between performance gain, cost, complexity, and durability is essential for practical implementation.
- **Experimental Validation:** Wind tunnel testing of an instrumented blade section equipped with the optimized VGs is a critical next step. Detailed flow measurements (e.g., via PIV) and force validation would confirm the CFD-predicted performance gains and provide reliable data for industrial adoption.

Pursuing these directions will help fully realize the potential of passive flow control, supporting the development of more efficient and economically viable wind energy systems.

6 Authors Contributions

1. **Moamen B., Saad.,** Conceptualized and designed the study, conducted the research and analysis, and wrote the manuscript.
2. **Adel K.,** Reviewed the results, critically revised the manuscript for intellectual and linguistic content, and supervised the research process.

7 Acknowledgments

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

8 Funding Declaration

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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