

Influence of Flow Control Devices on Aerodynamic Characteristics of Wind Turbine Blades: A Comprehensive Review

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Abstract

The growth of the wind energy sector has increased the need for enhanced techniques with the goal of improving the efficiency and reliability of wind turbines. As the size of wind turbines increases, there is a noticeable increase in energy loss, problems with fluctuating loads, and structural damage. This suggests that effective techniques need to be implemented in order to improve their efficacy. Methods for flow control, including passive and active flow control techniques, have been shown to be successful in enhancing lift-to-drag ratios, minimizing flow separation, and controlling boundary layer behavior. In the context of wind turbine applications, this review examines the aerodynamic effects associated with various flow control methods. Recent findings indicate that passive flow control devices exhibit simplicity and robustness, while active flow control methods allow adaptive, real-time control under varying wind conditions. This article presents a comprehensive overview of flow control methods for wind turbines, emphasizing their advancement, efficiency, and challenges. This review concludes with significant findings, lift enhancement of various flow control devices and their Technology Readiness Level (TRL), and possible avenues for enhancing aerodynamic efficiency and turbine performance longevity. Optimizing flow control systems, lowering implementation costs, and enhancing their flexibility under challenging operating situations should be the main goals of future study.

Keywords: Flow control, load alleviation, aerodynamic optimization, boundary layer control, biomimetics

INTRODUCTION

The global fossil fuel source has been rapidly depleted over the past few decades, and environmental concerns have increased. As a result, eco-friendly and renewable energy sources have become the main focus for global energy safety, and more attention has to be given to renewable energy sources, such as solar and wind. To ensure sustainable electricity generation, renewable energy sources, including hydro, solar, wind, biomass, tidal, and geothermal, must be improved. According to the International Renewable Energy Agency [1], global renewable-power capacity surged to 4448 GW by the end of 2024, marking a 15.1 % increase and accounting for 46% of total installed electricity-generation capacity worldwide. Renewables accounted for 92.5% of new worldwide power capacity in 2024, driven primarily by expansions in solar energy (452 GW) and wind power (113 GW) [1].

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According to the Global Wind Energy Council [2], global wind power capacity reached approximately 1,136 GW by the end of 2024, with offshore installations surpassing 80 GW and onshore capacity exceeding 1,050 GW. This marks an 11% annual increase, largely driven by expanding offshore development and steady

onshore growth averaging 6-7 % per year. The percentage of different renewable energy sources in the Global Renewable Energy (GRE) capacity is presented in Figure 1 (a), and the historic development of new installations with a five-year new Global Wind Energy (GWE) capacity forecast. This projected growth in wind energy has been accompanied by an increasing demand for larger and more powerful turbines. Modern multi-megawatt wind turbines at present feature rotor diameters exceeding 300 m, with power output capacity reaching up to 26 MW, as shown in Figure 1(b) [2].

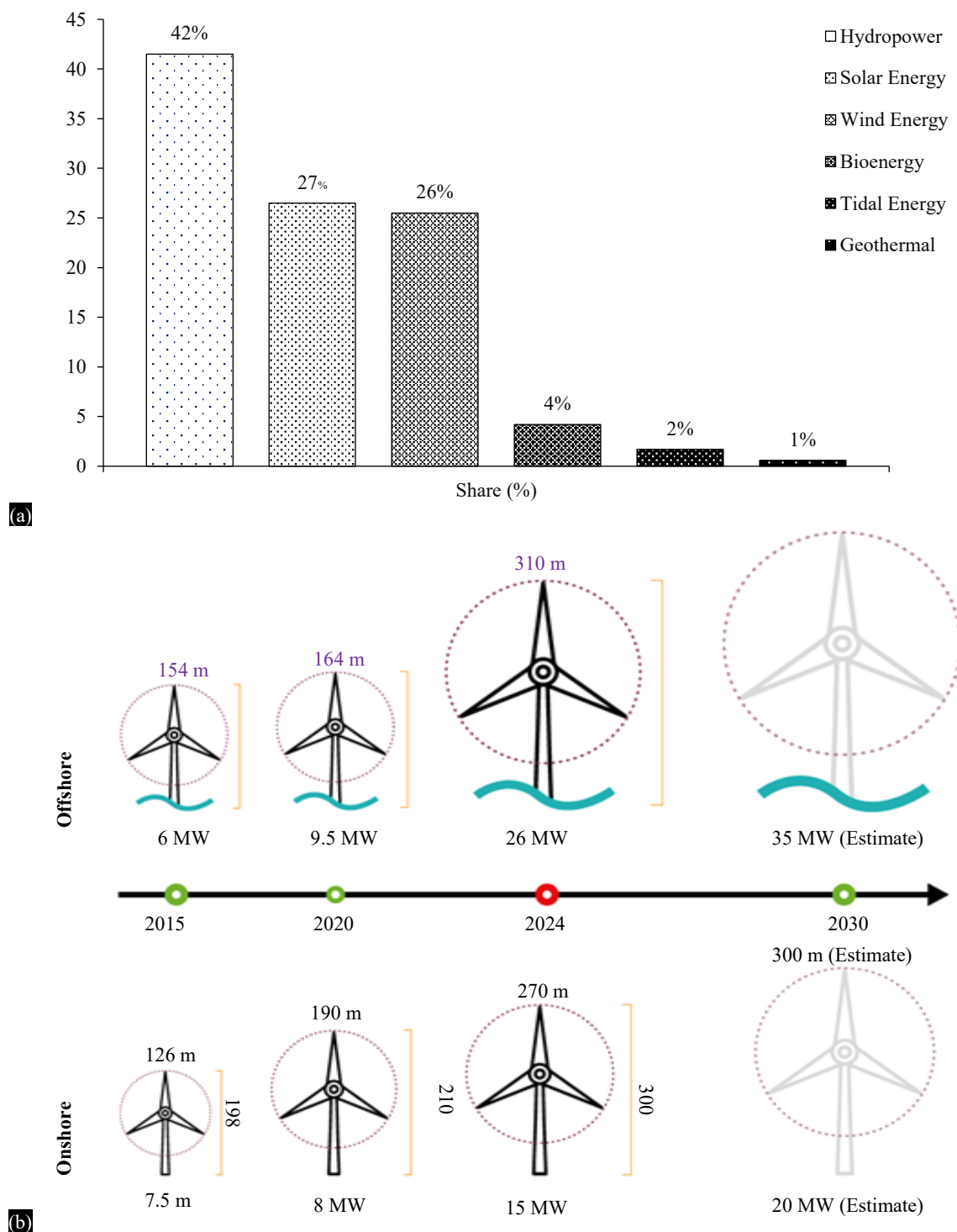


Figure 1. (a). Distribution of global renewable energy (2025) [3], (b). Trend of onshore and offshore turbine size [2].

Table 1. Literature review of the various flow control devices.

S.N.	Flow control technique	Categorization	References	Key results
1	Vortex Generators	Passive	[4]	The maximum lift coefficient increased by 21% and the stall angle was delayed by 17%
2	Suction	Active	[5]	The lift to drag ratio increases (0.4-1.8) with the increase of the suction coefficient (C_q)
3	Synthetic jets	Active	[6]	Synthetic jets significantly reduced the size of the recirculation bubble
4	Periodic excitation	Active	[7]	Excitation increases the lift by 50% compared to the lift of the baseline in post-stall conditions.
5	Blowing	Active	[8]	Increased the lift-to-drag ratio by 17 per cent at an angle of attack of 18°
6	Surface wrinkling	Passive	[9]	Drag reduction of up to approximately 20%, particularly when the aspect ratio of the riblets is close to unity.
7	Riblets	Passive	[10]	Riblets reduce total drag by 6%, 5%, 8.5%, and 9.5% for sweep angles of 0° , 15° , 30° , and 45° , respectively.
8	Morphing/ geometrical profile modification	Passive	[11]	The average tangential force can be increased by approximately 35% in the steady state case and 40% in the oscillating case
9	Surface modification	Passive	[12]	The 2D surface modification (groove/ramp) reduces the separation-bubble size by modifying the Kelvin-Helmholtz instability
10	Blowing and suction	Hybrid	[13]	Suction boosts lift by strengthening the low-pressure zone on the upper surface, whereas blowing is less effective and often raises drag
11	Plasma actuation	Active	[14]	The actuator increases lift by about (≈ 0.25 -0.30) at the optimal frequency in leading-edge separation conditions.
12	Leading-edge protuberances	Passive	[15]	Lift increases by approximately 81% when turbulence intensity rises from 0.51% to 4.92% at $\alpha = 15^\circ$ for the small protuberance.
13	Dimpled Cylinder	Passive	[16]	A dimpled cylinder reduces drag by approximately 10–30%, while at $Re \approx 79,920$, the reduction is $\sim 30\%$.
14	Surface roughness	Passive	[17]	A 20% reduction in the drag coefficient for the rough cylinder, however 30% reduction for the dimpled cylinder
15	Ion wind	Active	[18]	Ion wind alters the wake structure behind a circular cylinder, leading to a reduction in pressure drag by $\sim 60\%$.
16	Plasma actuation	Active	[19]	A reduction of up to 30% in drag can be achieved by using double actuators.
18	Helical groove	Passive	[20]	Increasing the start angle of helical grooves can achieve a drag reduction of 30% and a noise reduction of 6 dB.
20	Rectangular grooves	Passive	[21]	The presence of rectangular grooves on cylindrical buildings significantly narrows the wake width, reduces the mean and fluctuating pressure.
21	Micro-dimples	Passive	[22]	The dimple patterns could decrease the skin friction by the reduction of the wall shear stress and reduce the profile drag by about 3-5%.
22	Suction	Active	[23]	Suction gives the strongest flow control when a wide slot (1% chord) is placed downstream, and it increases lift by $\sim 25\%$.
23	Inward dimple	Passive	[24]	An inward circular dimple with a diameter equal to 8% of the chord length shows 18% improvement in optimal performance efficiency in the Darrieus vertical axis wind turbine.
24	Vortex Generators	Passive	[25]	Vortex generators control dynamic stall by generating streamwise counter-rotating vortices, effectively delaying the stall by 5-10%.
25	J-shaped aerofoil	Passive	[26]	J-shaped profiles in vertical-axis wind turbines enhance aerodynamic performance, with an increase in output power by 20% at optimum tip speed ratios.
26	Leading-edge serrations	Passive	[27]	Leading-edge serrations on vertical-axis wind turbine blades enhance power output by 18.3% at low tip-speed ratios (TSR = 2).

S.N.	Flow control technique	Categorization	References	Key results
27	Trailing edge flap	Active	[28]	Trailing edge flap on vertical axis wind turbine increases the peak power coefficient by 10% and effectively eliminates dynamic stall
28	Gurney flaps	Passive	[29]	The Gurney flaps at 1.4% of the chord and 2.2% of the chord increased lift by 23% and 37% respectively.
29	Gurney flaps	Passive	[30]	The serrated Gurney flap enhances the aerodynamic performance of vertical-axis wind turbines, outperforming the plain Gurney flap by 13.9% when the flap height was 6% of the chord.
30	Riblets	Passive	[31]	Riblets reduce viscous (skin friction) drag by up to 16% at a 6° angle of attack
31	Vortex generators	Passive	[32]	Shark scale-inspired vortex generators delay stall by 3°, boost lift by 18.37%, outperforming conventional vortex generators in aerodynamic efficiency.

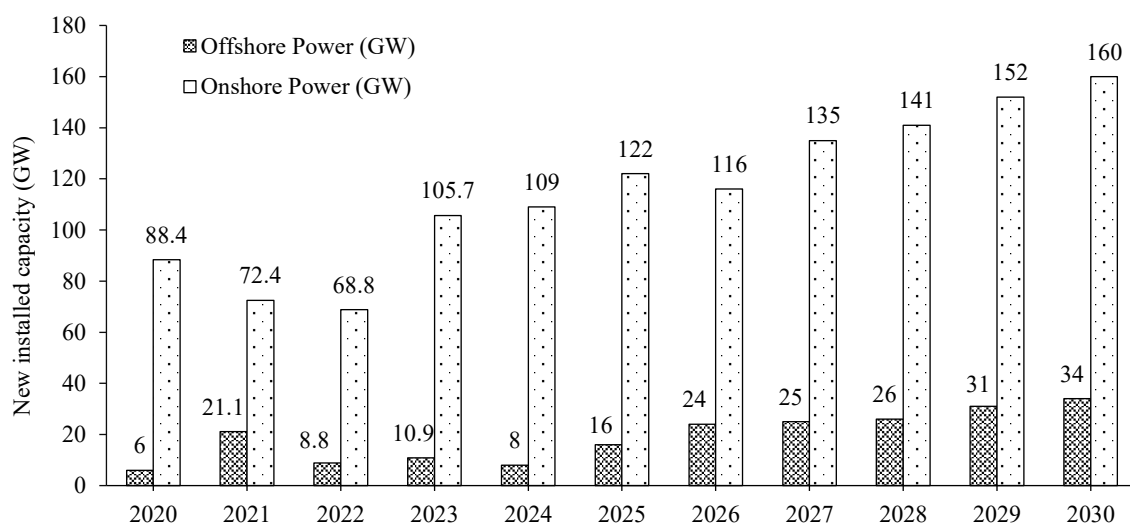


Figure 2. Capacity forecast of newly installed global wind energy (GWE) [2].

Figure 2 shows the capacity forecast of newly installed global wind energy (GWE). The constant increase in the size of wind turbines makes it very difficult to deal with the ultimate and fatigue loads on the blades. Multi-megawatt turbines, which work several hundred meters above ground level, are especially affected by stronger air turbulence, gust-induced oscillations, wind shear (both horizontal and vertical), blade-tower interaction, and yaw or tilt misalignment effects. In addition, the large mass of these blades causes strong cyclic structural loads caused by gravity. To reduce these negative impacts, it is important to use advanced load-alleviation and fluctuation-damping management systems to ensure that operations are safe and that energy is captured efficiently. Effective flow-control methods around the blade can greatly improve its aerodynamic and aeroacoustics properties and lower both extreme and fatigue loads.

This study investigates different flow-control methodologies designed to improve the efficacy of wind turbines. Figure 3 shows different active and passive flow control methods used on wind turbine blades to improve aerodynamic efficiency, boost power output, make operations more stable, lower loads, and cut down on noise. Figure 4 shows the percentage of shared literature. This study comprehensively investigates different flow-control systems, focusing on their progress, basic concepts, and the benefits and problems in wind turbine applications. It also compares their ability to improve aerodynamics, especially in lift modulation, and examines how mature they are based on the technology readiness level (TRL) categorization. Insights derived from this review are expected to guide future advancements in designing efficient, reliable, and scalable flow-control strategies for next-generation wind turbines. Table 1 presents a literature review of various flow control devices.

PERFORMANCE ENHANCEMENT DEVICES

The various performance enhancement devices (blade add-ons) commonly used for wind turbine blades are shown in Figure 5; certain devices are designed to enhance the performance of wind turbine blades through passive operation, requiring no external energy input. Serrations on the trailing edge, for example, aid in lowering the noise produced by airflow interaction. Vortex generators are used to slow down flow separation, which makes the airflow over the blade surface smoother and makes the blade more aerodynamically efficient. Experimental designs, such as wing-tip sails, also attempt to make it easier for air to flow behind the rotor [33]. Table 2 shows an overview of commonly deployed wind turbine blade add-ons, as shown in Figure 2.

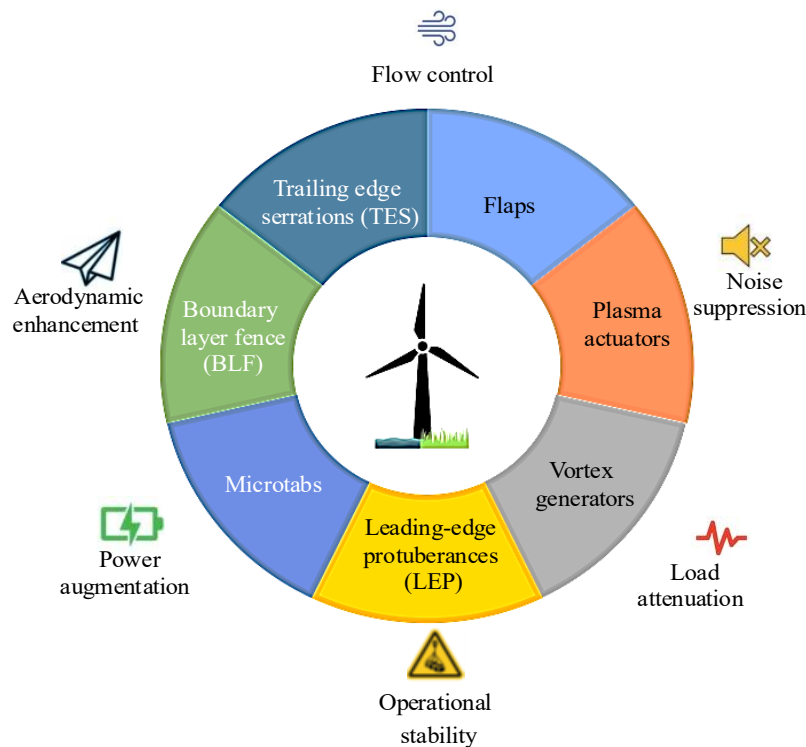


Figure 3. Flow control mechanisms used in a wind turbine.

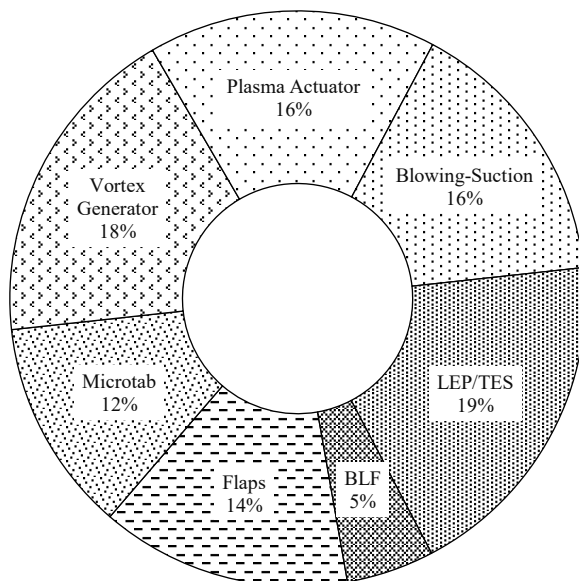


Figure 4. Literature share of reviewed flow control devices.

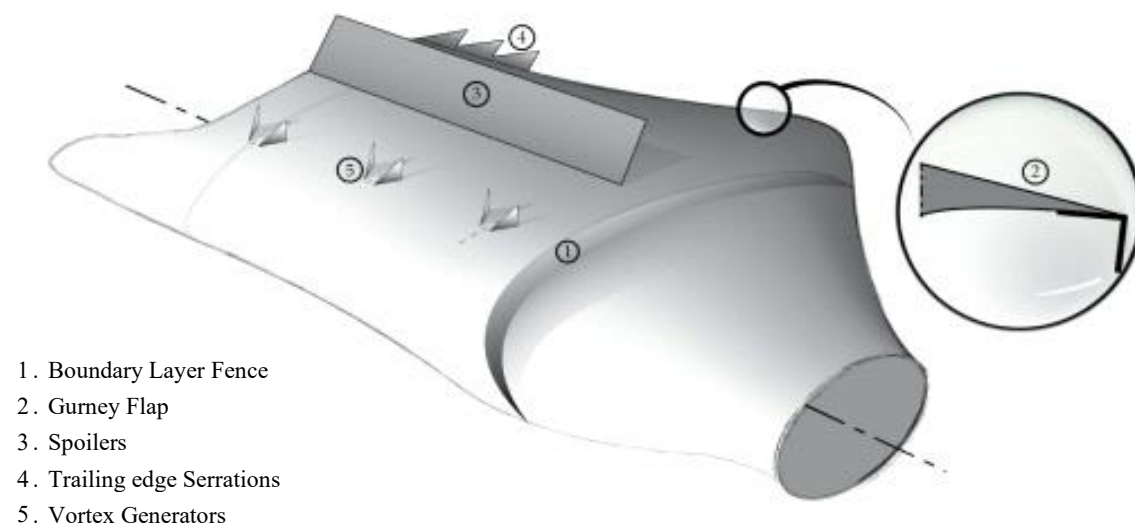


Figure 5. A representation of a horizontal axis wind turbine blade with different flow control devices.

Table 2. Overview of commonly deployed wind turbine blade add-ons, as shown in Figure 2.

S.N.	Flow control techniques	Purpose
1	Boundary layer fence	To stop disturbed airflow near the blade's root from spreading to other parts, keep the airflow smooth and efficient.
2	Gurney flap	Increase sectional lift by increasing effective airfoil camber.
3	Spoilers	Improve the lift and twisting force (torque) generated by the inner part of the blade
4	Trailing edge serrations	To reduce the noise created by airflow as it leaves the edge of a blade, making it quieter
5	Vortex generators	To mitigate flow separation, enhance load stability, and optimize annual energy production

Flaps

Wind turbines use flaps as passive flow-control devices that change the blade's local camber in real time. This prevents the flow from separating too quickly, increases lift, and reduces aerodynamic losses when the wind is not steady. Flaps change the effective angle of attack along the blade surface, which makes it easier for airflow to reattach during operations that are prone to stalling. This improves the turbine's overall power coefficient and stability. The adaptive flap is a passive, self-adjusting flow control device that prevents flow separation in high-solidity Vertical Axis Wind Turbines (VAWTs). It can improve aerodynamic torque and power output by up to 45% at low Tip Speed Ratios (TSRs) [34]. Shorter flaps that are placed correctly on the blade respond better and work consistently across flow regimes. Longer or forward flaps, on the other hand, make the blade less efficient at high TSRs because they take longer to retract. Figure 6. shows self-activated movable flaps that were inspired by bird feathers, function as passive flow control devices that stop flow reversal, which delays flow separation and increases lift by up to 15% without requiring external energy [35]. Trailing-edge flaps significantly alleviate unstable aerodynamic loads in floating wind turbines, diminishing blade-root fatigue and platform pitch motion by up to 40% while preserving aerodynamic efficiency [36].

Trailing-edge flaps reduce unsteady aerodynamic loads on large wind turbine blades by up to 13% in root bending moment, 16% in tip deflection, and 11% in tower fore-aft motion, improving fatigue performance without affecting aerodynamic efficiency [37]. When combined with passive aeroelastic tailoring (bend-twist coupling), the integrated flap-tailoring approach achieves nearly 40% reduction in dynamic loads. Trailing-edge flaps positioned between 70–75% of the blade span augmented the

annual average power by as much as 8.84% and diminished the blade root bending moment by 2.9%, demonstrating their dual function of power improvement and load alleviation [38]. The flaps can enhance power output and reduce the Levelized Cost of Energy (LCOE) [38], and lower mechanical loads while making stable power generation [39]. Optimized trailing-edge flaps reduced the blade root moment power spectral density by up to 97% at 1P frequency and smoothed generator power fluctuations by up to 42%, significantly enhancing load alleviation and power stability in smart rotors [39]. The study [40] concludes that the Gurney Flap (GF) functions as a passive flow-control device that enhances the aerodynamic behavior of Darrieus wind turbines primarily at low tip speed ratios (TSRs) by modifying the near-trailing-edge flow structure. When attached to the trailing edge of a NACA 0015 aerofoil, the GF generates counter-rotating vortices (a schematic shown in Figure 7) that increase the pressure difference between the suction and pressure surfaces, thereby delaying flow separation and improving lift and torque generation at moderate TSRs (around 2.5); however, as TSR increases beyond 3.5, the same vortex structures induce excessive drag and early flow detachment, leading to performance deterioration and even negative C_p values due to wider turbulent wakes [40]. A comparative analysis [41] indicates that gurney flaps greatly enhance lift, flow attachment, and torque smoothness in Darrieus turbines operating at low to moderate TSRs by stabilizing the trailing-edge flow and reducing dynamic stall. However, their aerodynamic advantages decrease at higher TSRs because of increased drag and wake turbulence, which restricts their best use to low-wind or self-starting scenarios.

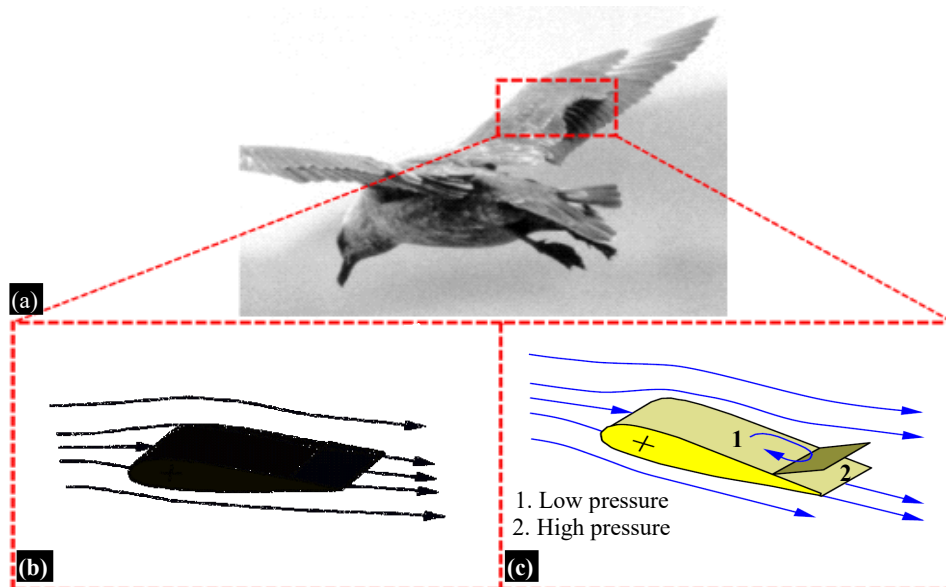


Figure 6. (a) A bird's wing with popped-up feathers [35] (b) Adaptive flap at low angle of attack (c) popped up adaptive flap at higher angle of attack [34].

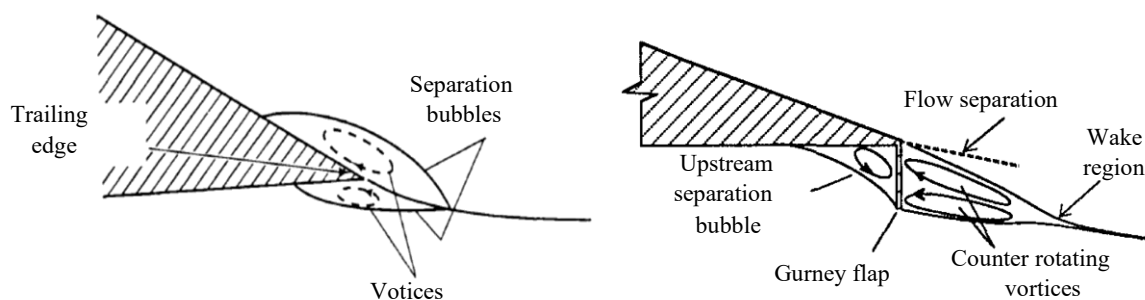


Figure 7. Schematic representations of the trailing edge flow field with a rigid flap and gurney flap [44].

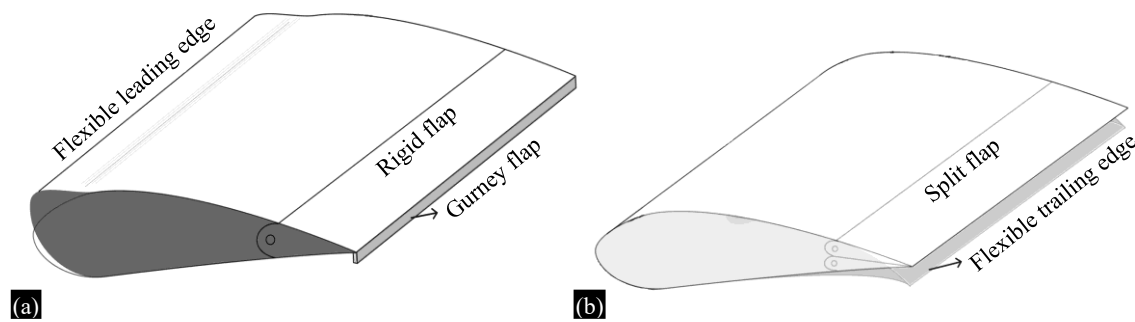


Figure 8. (a) and (b) Illustrations of different flap configurations used for flow control [42].

Review [43] shows that gurney flaps are only useful in low-speed, self-starting, and unstable flow situations where torque stability and flow attachment are more important than maximum efficiency, as they produce additional drag at high speeds. The split flap operates similarly to a Gurney flap but includes a hinge mechanism that allows it to deflect upward or downward, as shown in Figure 8. This setup offers the advantage of being deployable only when needed, potentially reducing drag. The split-flap configurations (hinge line @ $1h$ means the flap pivots around a point located a distance equal to one flap height ahead of the trailing edge, hinge line @ $1.5h$ means the hinge is placed slightly farther forward, at 1.5 times the flap height) generate a lift coefficient nearly identical to that of a Gurney flap with a height of 1.5% of the chord length for NACA4412 airfoil, as shown in Figure 9. This means that the split flaps can produce almost the same increase in lift for a given angle of attack as the Gurney flap [44].

A study on the serrated Gurney flap [45], with a width of $6.7\%c$ and a height of $0.8\%c$, demonstrated enhanced lift, delayed stall by approximately 3° , and reduced radiated noise by 0.51 dB and 4.40 dB at angles of attack of 12° and 20° , respectively, by weakening vortex separation and stabilizing the flow field. The slit-modified Gurney flaps (GF) on vertical axis wind turbine (VAWT) blades lead to notable aerodynamic performance enhancement [46]. The slits introduce small-scale vortices that dissipate large coherent flow structures in the near wake, reducing drag by approximately 8% and increasing the lift-to-drag ratio by 6.5% at medium Tip Speed Ratios (TSRs). Although lift decreases slightly ($\approx 2\%$) due to airflow through the slits, the overall power output improves by 1.5%, 6.5%, and 11.3% for low, medium, and high TSR regimes, respectively.

The goal of using Adaptive Trailing Edge Geometry (ATEG) on wind turbines is to control stalls and reduce loads. When fully deflected, the flexible flap system showed a strong ability to change lift, resulting in a significant drop in lift that could help slow down the rotor of a wind turbine. However, when the angle of attack was high, the system became less stable aerodynamically, which means that in real-world situations, there may be a trade-off between lift control and structural stress [47]. ATEG devices, including flexible or morphing flaps, attain equivalent lift enhancement as traditional rigid flaps; however, they require considerably smaller deflection angles; two distinct ATEGs are shown in Figure 10.

ATEGs necessitate a 30% reduction in deflection compared to conventional flaps for equivalent lift augmentation, as depicted in Figure 11. Morphing trailing-edge flaps produce lifts that are almost equal to the lift produced by the hinged flap, providing a more efficient load-control mechanism for wind turbines [48]. Gurney flaps set up static with a height of 4% of the chord caused the vortex to move the most laterally. This displacement dramatically changed the vortex behavior near the flap edge, providing crucial insights for the control of wake while minimizing aerodynamic loads [49]. The enhancement of lift is greatly influenced by the size and placement of the Gurney flaps. The position along the chord and the size of the flap exhibits a linear relationship with the enhancement of lift [50].

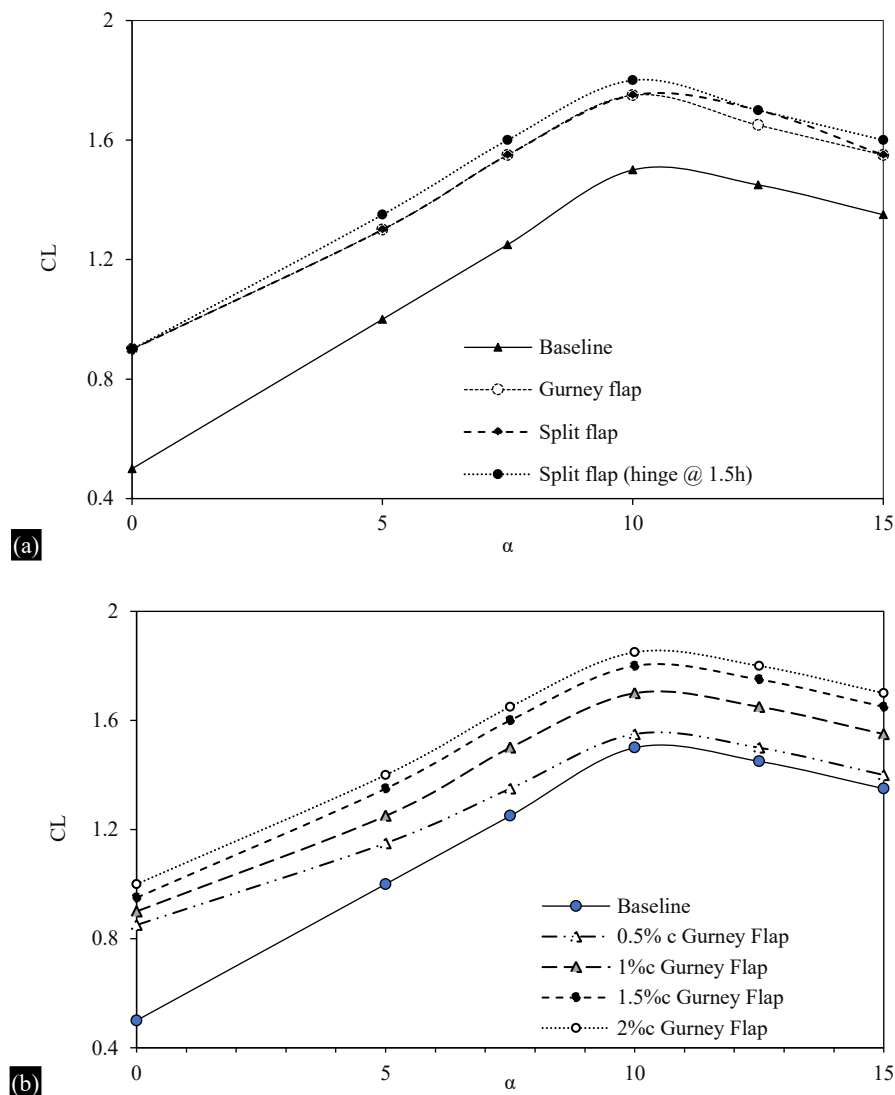


Figure 9. Lift characteristics of Gurney flap and split flap configurations [44]. (a) Comparison of Gurney Flap and Split Flap Configurations; (b) Effects of Gurney Flap Height on Lift Coefficients

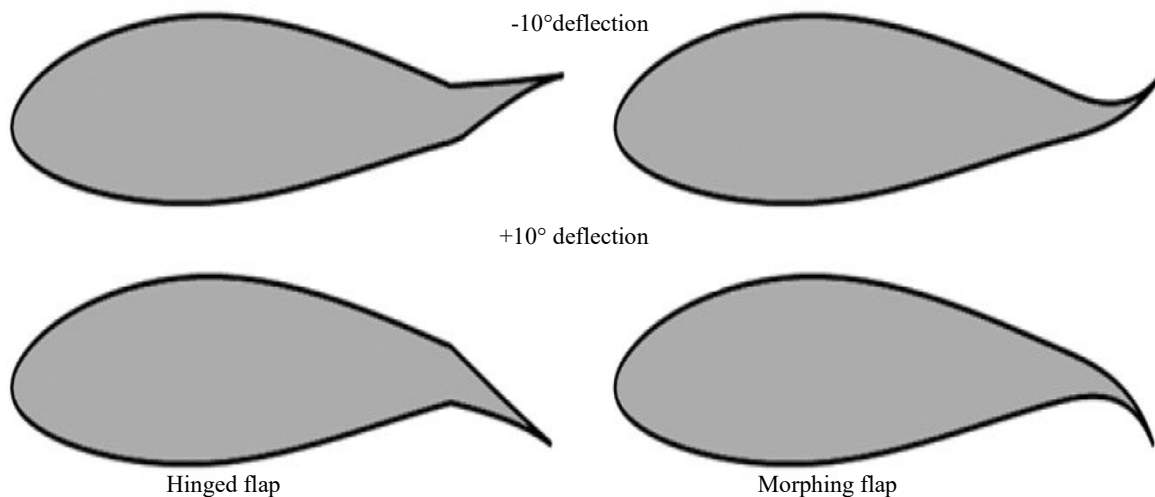


Figure 10. Conventional hinged flap and morphing flap geometries [48].

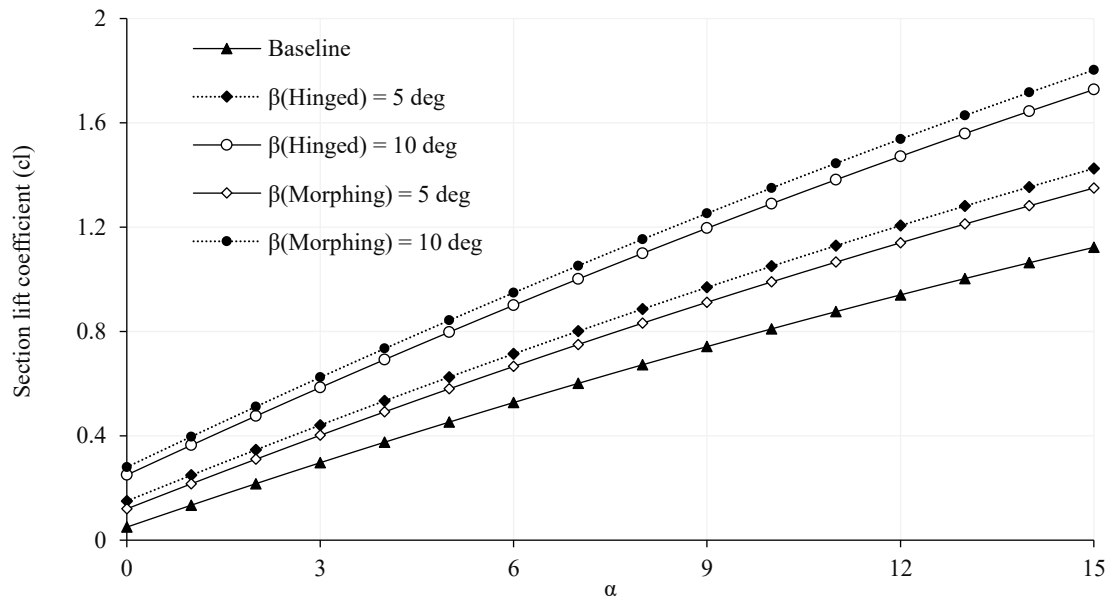


Figure 11. Lift coefficient of blade section with hinged and morphing flaps ($Re = 6.44 \times 10^6$) [48]

Challenges

The size of rigid flaps and the conditions under which they function restrict their performance. Although increasing the dimension of the flap increases lift, it also adds weight and drag, which could affect the overall efficiency. The size of the flaps must be larger than the thickness of the boundary layer to work at their best, particularly at higher angles of attack. This implies that the size of the rigid flap cannot be decreased without compromising its functionality. Aerodynamic instabilities brought on by the sudden change in camber caused by the increased flap angle lower the lift. Despite these constraints, it is challenging to improve the configurations of rigid flaps under many aerodynamic conditions, particularly for high efficiency. The effectiveness of flaps with adaptive trailing edge geometries (ATEGs) is limited by their significant energy consumption. The frequent structural changes in ATEGs may shorten their lifespan and cause fatigue. Another challenge is that environmental factors and repeated stresses should not damage the integrity and operation of these components.

Conventional gurney flaps increase lift, but their design inherently increases drag. These gurney flaps are not appropriate for unsteady flow conditions. Finally, the split-flap configuration increases the drag in unstable flow conditions owing to complicated wake interactions.

Emerging Solutions

Active gurney flaps signify an advancement in flow control techniques, as they may modify their height or deployment according to flow conditions, in contrast to rigid flap configurations. In addition, these flaps are more suitable for both steady and unsteady conditions due to their dynamic adjustments. Employing lightweight, high-strength materials, such as carbon fiber composites, mitigates the structural constraints of active gurney flaps. The implementation of flexible trailing-edge flaps has become more efficient through the incorporation of precision control systems alongside aeroelastic modelling. Their capacity to substantially reduce structural fatigue while maintaining aerodynamic efficiency makes them suitable for high-stress applications in wind turbine blades.

The progression of hybrid designs utilizing active flow control methods, including boundary layer suction and blowing, in conjunction with the double-split flap configurations depicted in Figure 12, exemplifies an efficient strategy for flow management. These innovations augment the overall lift efficiency, reduce drag, and optimize the management of flow separation.

Microtabs

The use of microtabs as aerodynamic devices was first suggested by Van Dam. As shown in Figure 13, microtabs are tiny aerodynamic devices placed on the surface of an aerofoil or blade to alter airflow properties. Microtabs are placed on both sides of the aerofoil, just upstream of the trailing edge and at a right angle to the surface. Microtabs usually have a very small height, from 1% to 2% of the chord length, which is quite close to the thickness of the boundary layer. This makes them work better by delaying flow separation and increasing lift. The micro tab alters the location of flow separation, moving it from the airfoil's trailing edge to the lower edge of the tab. This modification results in a beneficial recirculating flow pattern behind the tab, as depicted in Figure 14. This shift fundamentally modifies the camber of the airfoil and enhances the aerodynamic characteristics of the airfoil without requiring a substantial redesign of its structure.

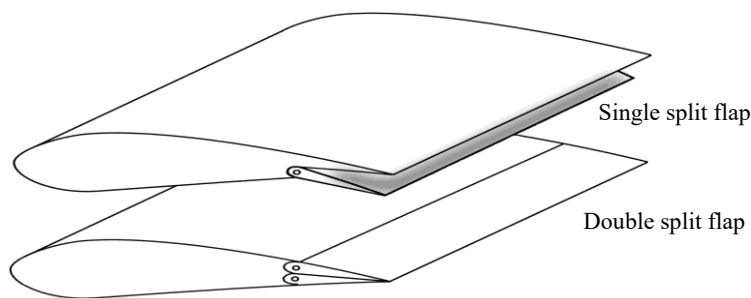


Figure 12. Conceptual design of ATEGs with single and double split flap [42].

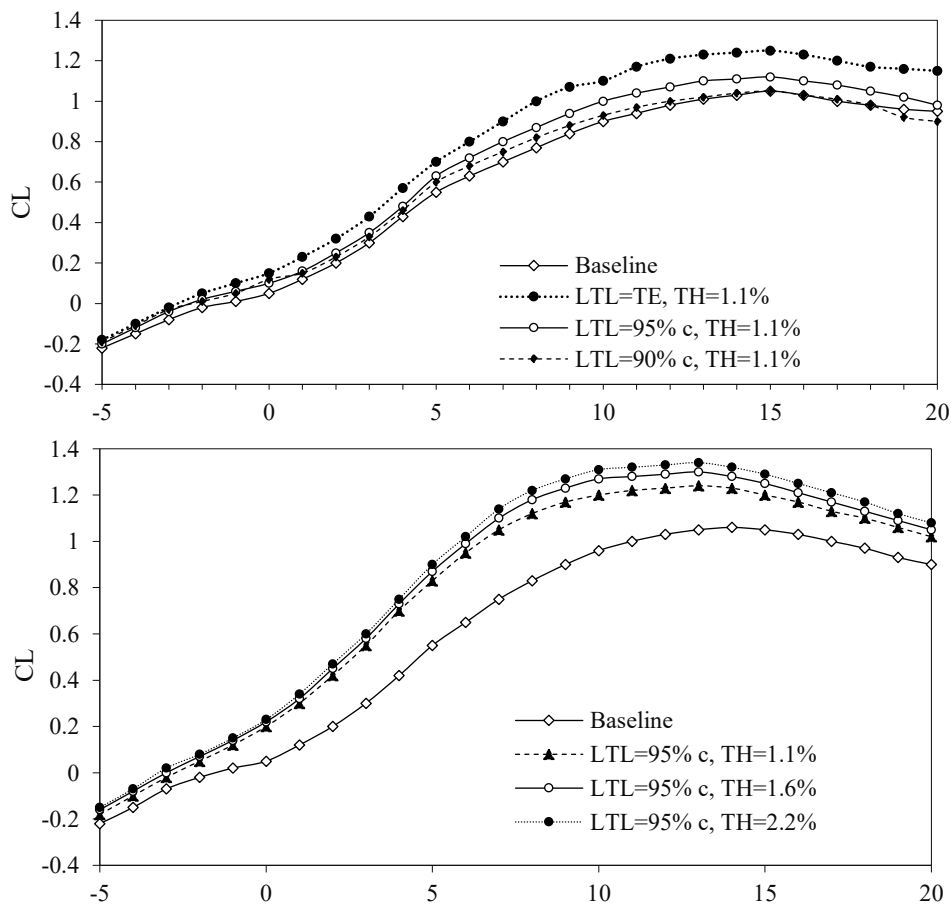


Figure 13. (a) Lift coefficients for different locations of microtab (b) Lift coefficients for different heights of microtab; TE – Trailing-edge; LTL – [Lower (pressure) surface Tab Location]; TH – Tab Height.

The microtabs substantially enhance aerodynamic performance, achieving an increase in the lift coefficient (ΔC_L) of up to 0.5 under certain operating conditions. The lift characteristics for the different microtab configurations are illustrated in Figure 15. Microtabs are a highly efficient method for aeroelastic control of wind turbine blades. Simulations revealed that actuation in microtabs can reduce root flap bending moment oscillations by up to 46% at dominant loading frequencies (2P–5P), greatly reducing fatigue loads. This reduction results in a 35% increase in turbine blade fatigue life. Deployment of microtabs with a height of 1% chord produces an immediate change in the lift coefficient of approximately 0.2, sufficient to counteract a 12% change in freestream velocity. Sequential activation of spanwise tab segments allows smoother, gust-matched load variation and prevents impulsive lift changes. The microjet operating at 60 m/s demonstrates a power coefficient that exceeds 29% in low wind conditions. In contrast, the 2% chord microtab demonstrates enhanced performance in high wind scenarios, offering a more practical and energy-efficient solution for load control when compared to microjets. A comprehensive study found that when microtabs are deployed on both upper and lower surfaces, an increase in the lift coefficient has been found from literature, are $\Delta C_L = 0.3$ for a tab height to chord ratio ($T_h/c=1\%$), with a maximum increase of $\Delta C_L = 0.4$ for $T_h/c=2\%$.

Miniature trailing-edge effectors (MiTEs) or microflaps are tiny, movable flaps positioned at the trailing edge of an airfoil or blade, as shown in Figure 16. These flaps are used to control aerodynamics and modify the airflow. Owing to their extremely small size, typically 1% to 5% of the chord length of the blade), they efficiently influence the aerodynamic forces operating on the blade with little structural consequence.

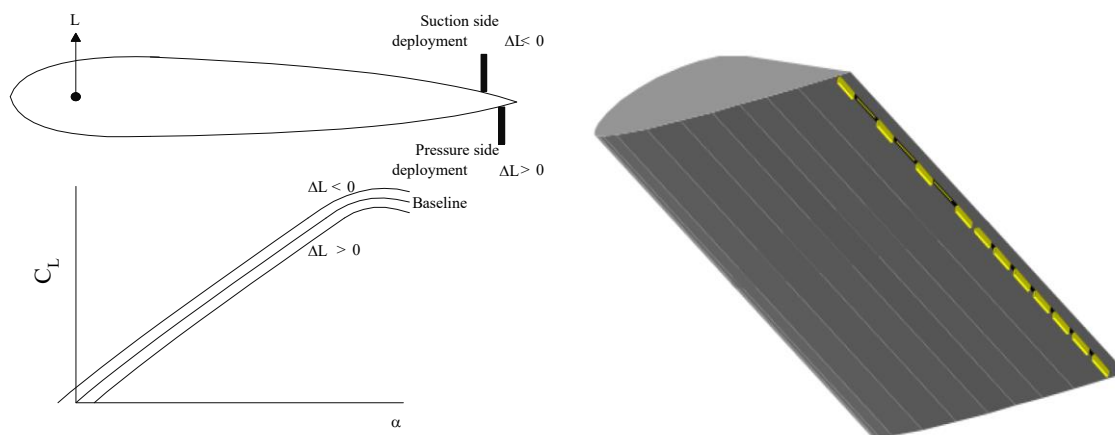


Figure 14. (a) Microtab concept based on the Kutta condition, (b) Conceptual wing section - courtesy of professor case van dam.

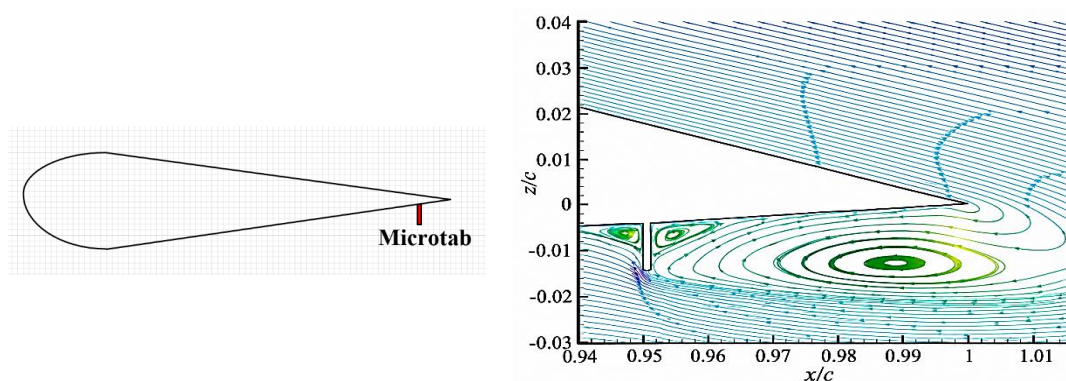


Figure 15. Schematic design of an aerofoil with Microtab (left), Computational Streamlines for GU25-5(11)-8 airfoil with tab ($h/c = 0.0$) (right).

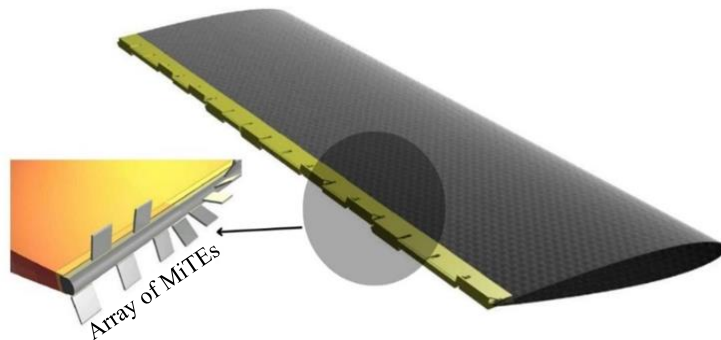


Figure 16. Conceptual design of aerofoil with MiTEs.

There are three positions for microtabs: neutral (retracted), upward, and downward. Their main purpose is to change the way airflow behaves by causing flow separation upstream and releasing two counterrotating vortices downstream. The use of MiTEs affects lift in many ways. If MiTEs are moving up, it decreases lift by changing the upward force on the aerofoil, while moving them down increases lift by making good airflow patterns stronger. When MiTEs are in their neutral position, they have very little effect on how well an object moves through the air. MiTEs are a useful tool for accurately calibrating aerodynamic parameters in situations when lift control is very important because of their features. Research has investigated their capability for wake-vortex mitigation, vibration of rotor and noise reduction, their response to aerodynamic behavior under supersonic flow, and the aerodynamic performance of segmented MiTEs. The study found that a MITE placed about 10% ahead of the trailing edge can create a moment coefficient change of 0.03, which is almost the same as a standard flap with a 2.3° deflection. This shows that even a small device can provide strong aerodynamic control. In rotor models, MiTEs oscillated at a frequency of 4/rev and cut down on periodic vertical (4P) loads by almost 80%. This shows that they can greatly improve helicopter vibration control and aerodynamic efficiency, and maybe even in wind turbines as well.

Challenges

Microtabs are attractive because they are small, mechanically simple, and can change the trailing-edge circulation with minimal actuation; however, several hard practical and aerodynamic challenges limit their deployment on modern wind turbines. Microtabs interact strongly with the boundary layer and separated shear layers over a wide range of Reynolds numbers and local angles of attack encountered along a rotor blade; this makes their net benefit highly sensitive to tab height, spanwise position, and local inflow (turbulence, yaw, and unsteady gusts), so suboptimal sizing or placement can actually increase drag or excite unsteady loads rather than reduce them. Structurally and mechanical-integration problems include the fatigue and reliability of many small actuators on a rotating blade (exposure to rain/ice, erosion, and contamination), routing power/control to distributed devices across a spinning hub and ensuring fail-safe retraction so that a stuck tab does not cause large asymmetric loads. Control challenges arise when microtabs are used for active load control: sensing and closed-loop timing must be very fast and robust to distinguish 1P/3P components from stochastic turbulence, and controller/actuator bandwidth, latency, and slip/gearbox interactions constrain achievable performance. Finally, there are modeling and validation gaps: many promising computational fluid dynamics (CFD) or small-scale wind-tunnel results do not translate directly to full-scale rotating blades because of three-dimensional rotational effects, dynamic stall, and aeroelastic coupling; therefore, uncertainties in predicted power, fatigue, and system-level benefits remain high.

Miniature trailing edge effectors (MiTEs) face several challenges related to their aerodynamic performance, durability, and operational complexity. One of the primary issues is their sensitivity to unsteady aerodynamic effects caused by dynamic wind conditions, such as turbulence and gusts. Another challenge is the noise produced by MiTEs turbulent interactions with airflow, which can worsen environmental noise concerns, particularly in densely populated regions. Integration with

advanced control systems, ensuring reliable actuation mechanisms, and requiring maintenance throughout the turbine's lifetime are all operational challenges.

Emerging Solutions

Recent work has addressed the limitations above with a mix of improved design, hybrid passive/active hardware, and systems-level control approaches. On the design side, parametric studies and high-fidelity CFD with rotating-frame simulations have refined optimal microtab geometry, spanwise placement, and small-height scaling (typically $\approx 0.5\text{--}2\%$ chord) so tabs alter the effective camber without excessive drag; such design rules reduce sensitivity to operating point. Mechanically, simpler low-power actuators (shape-memory alloys, bistable springs, or small servos with fail-safe springs) and sealed, erosion-resistant tab housings improve durability; some architectures move to clustered or spanwise-distributed microtabs (fewer actuators covering the same effect) to cut wiring and failure modes. On control and sensing, researchers combine feedforward scheduling (based on rotor azimuth and precomputed aero maps) with a small number of distributed strain/pressure sensors or optical/local flow sensors to trigger only the tabs that will be effective, lowering bandwidth/communication demands.

Vortex Generators

Vortex generators (VGs) are small aerodynamic devices typically shaped as triangular or rectangular vanes installed on the suction side of an airfoil or blade, as illustrated in Figure 17. Positioned at an angle to the incoming airflow, these vanes interact with the flow by generating trailing vortices. These vortices transport high-momentum air from the free stream into the lower-momentum boundary layer, which is the thin layer of air near the surface of the blade.

This process reenergizes the boundary layer, making it more resistant to flow separation (a phenomenon where the smooth flow of air detaches from the surface), leading to a loss of lift and increased drag. Boundary layer separation results in flow reversal, almost zero shear stress, and loss of lift when low-momentum air is unable to overcome an unfavorable pressure gradient. Vortex generators prevent this separation by producing trailing, helically symmetric vortices that re-energize the boundary layer and maintain the flow. In high-lift aerodynamic applications, vortex generators greatly increase lift and decrease drag by postponing separation and stabilizing the flow.

The study using different configurations of vortex generators, shows that triangular vortex generators positioned at 40% of the chord length of the NACA 4415 airfoil ($X_{VG} = 0.4c$) optimally delayed flow separation, improving the maximum lift coefficient ($C_{L, \max}$) by 11.3%, and delaying stall to a higher angle of attack, while rectangular vortex generators positioned at 30% of the chord length ($X_{VG} = 0.4c$) improved the maximum lift coefficient ($C_{L, \max}$) by 16.3%.

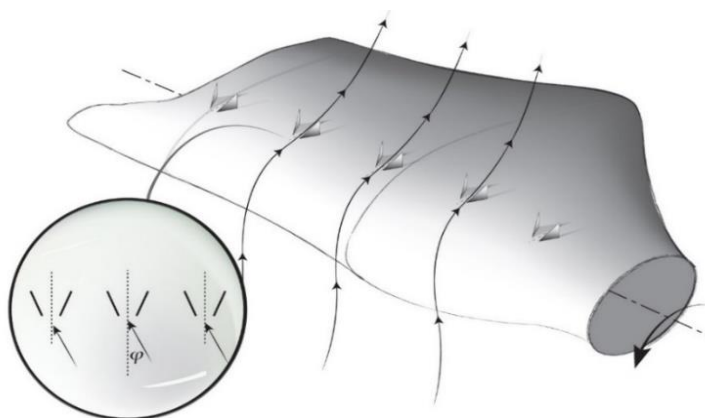


Figure 17. An array of triangular vortex generators mounted near the blade root of HAWT and schematized Skewed inflow(ϕ) relative to VGs.

Another important finding is that the maximum lift coefficient ($C_{L, \max}$) increased by 21.3%, and the stall angle was delayed to 17° in a tandem configuration that combined standard triangular vortex generators (VGs) with submerged VGs placed at 29% and 30% of the chord length, respectively. The results show that triangular vortex generators work best when they are placed at or near the flow separation area, which is usually around 40% of the chord, as shown in Figures 18 and 19.

A review illustrates the effectiveness of vortex generators (VGs) in flow control and the application of miniature VGs for managing separation control. This demonstrates a practical application of vortex generators in optimizing aerodynamic performance. In a canard airfoil configuration, vortex generators play a crucial role in re-energizing the boundary layer, thereby facilitating the reattachment of the flow.

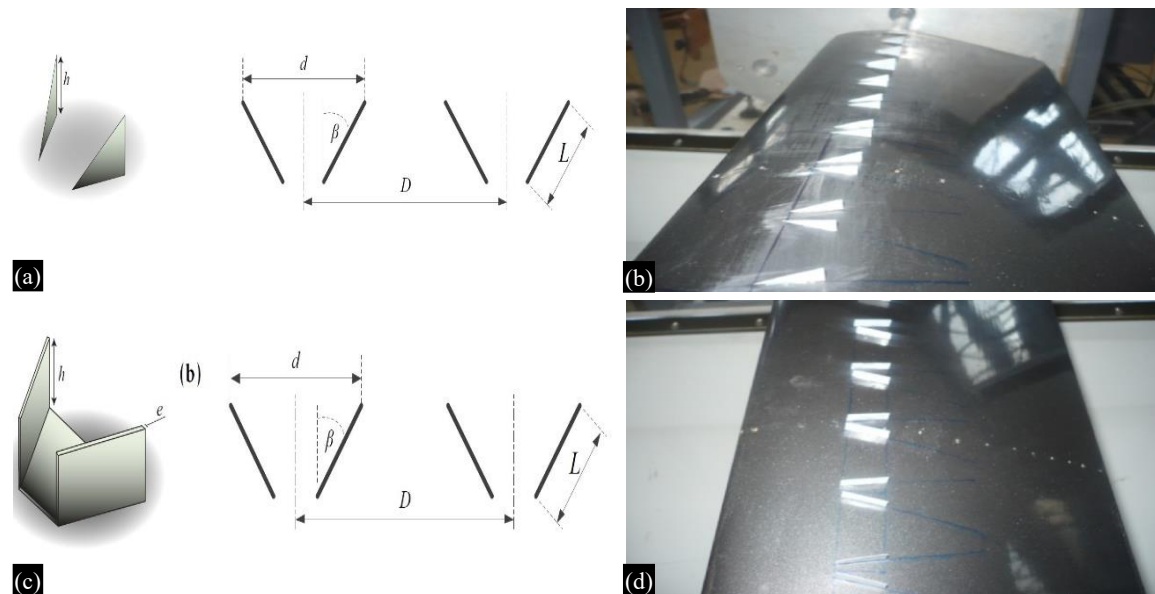


Figure 18. (a) Nomenclature of triangle vortex generator array [33], (b) Experimental setup of triangular vortex generator on NACA 4415 [4], (c) Nomenclature of rectangle vortex generator array [33], (d) Experimental setup of rectangular vortex generator on NACA 4415 [4].

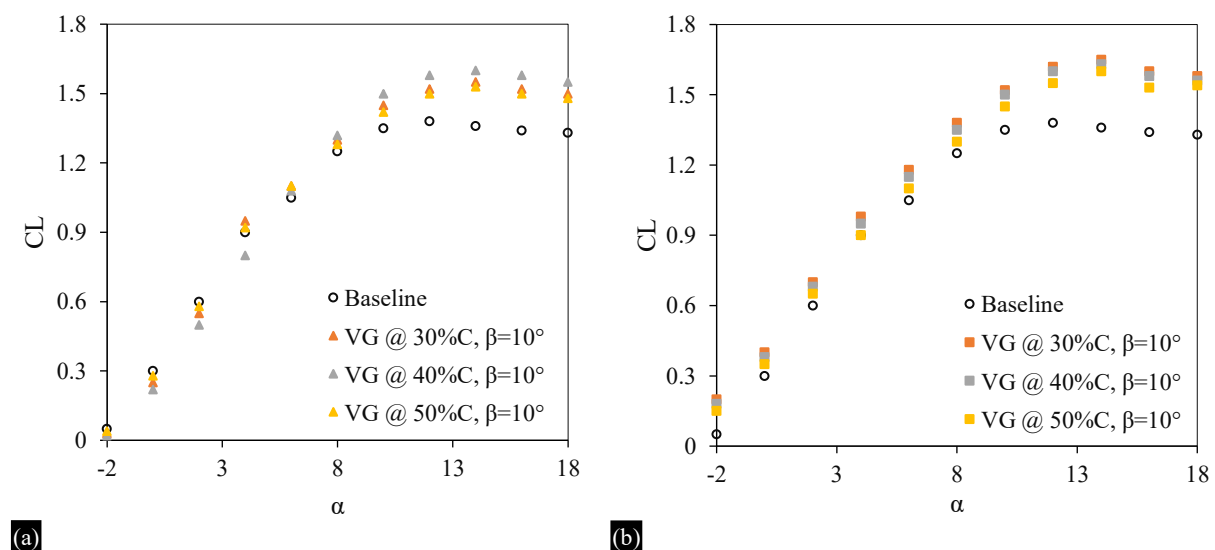


Figure 19. (a) Effect on (L/D) ratio of triangular vortex generators (left); (b) rectangular vortex generators (right) [4].

The boundary layer detaches at 55% of the chord; however, the vortex generator facilitates the reattachment of the separated flow at 70% of the chord. The installation of counter-rotating delta-type vortex generators (VGs) at 20% chord on the DU97-W-300 blunt trailing-edge airfoil significantly enhanced aerodynamic performance. Specifically, the maximum lift coefficient ($C_{L, \max}$) increased from 1.5 to 1.7, and the stall angle increased from 12° to approximately 17° , showing a 40% enhancement. The drag coefficient (C_d) increased slightly before stall due to added friction, but the post-stall drag was significantly reduced as the flow remained attached longer. Installing delta-wing vortex generators at $x = 0.2c$ on thick airfoils (CAS-W1-450, CAS-W2-350, CAS-W2-400) increased the maximum lift coefficient from 1.04 to 1.55 (one-row) and up to 2.02 with a two-row layout, while delaying stall from 12° to 24° , though with a minor drag rise ($\sim 8\text{--}10\%$) at low angles of attack. Installing counter-rotating rectangular vortex generators at 10% and 20% chord increased the maximum lift coefficient from 1.11 to 1.72, delayed stall from 14° to 18° , and improved torque by $\approx 45\%$, while reducing boundary-layer thickness and drag by up to 33% at an angle of attack of 18° .

A collaborative study between academic researchers and industry professionals aimed at evaluating effective techniques to measure the impact of vortex generators (VGs) on wind turbine power generation. Installing vortex generators (VGs) on full-scale 2 MW wind turbines resulted in an average power increase of 2.8 - 3.7% on complex terrain (and 1.6–1.8% on flat terrain), with site-specific variations up to 7% improvement, confirming that VGs effectively re-energize boundary-layer flow, delay separation, and enhance power capture under turbulent inflow conditions. Combining Gurney flaps (GFs) and vortex generators (VGs) provides a complementary passive flow control strategy that delays flow separation, enhances lift, and increases turbine efficiency by up to 4.8%, outperforming either device used alone. Similar results were obtained using these combinations.

Installing Leading Edge Vortex generators of diameter 6 mm, height 0.5 mm, and spanwise spacing 20 mm at 0.17% chord on an OA209 airfoil ($Re = 1.15 \times 10^6$) increased downstroke lift by up to 56%, reduced negative pitching-moment peaks by 38%, and lowered drag by 24-35% under deep dynamic-stall conditions, confirming that leading-edge VGs effectively disrupt large stall vortices and delay flow separation. Placing the vortex generators closer to the leading edge (at $0.1c$) raised the flutter cessation wind speed by approximately 10.76%, broadened the stall flutter's stable operating range, and lowered the flutter frequency by approximately 13.56%. Passive vortex generators effectively delay or even suppress dynamic stall in wind turbine airfoils by re-energizing the boundary layer, reducing hysteresis, and enabling faster flow reattachment, especially when larger VGs are placed closer to the leading edge (around $0.2c$). In a thick and flatback wind turbine airfoil, vortex generators significantly enhance flow stability and delay the onset of dynamic stall by maintaining boundary layer attachment during the upstroke phase and also increase lift overshoot and potential post-stall load fluctuations. In horizontal-axis tidal turbines, vortex generators significantly reduce unsteady hydrodynamic load fluctuations and enhance energy capture by suppressing flow separation and stabilizing surface vortices, achieving up to 43.95% reduction in thrust fluctuations and nearly 10% increase in power output under turbulent inflow.

Installing delta-wing VGs on the inboard 5–30 m span of the DTU 10 MW turbine blades delayed flow separation and increased local lift coefficient by up to $\approx 25\%$ at mid-span sections ($r = 24\text{--}30$ m), yielding 0.25–0.5 % higher total power output and smoother aerodynamic loading across the rotor. To gain insights into the wake physics of vortex generators, researchers used particle image velocimetry (PIV) to visualize the wake behind vortex generators (VGs) and studied how the wake evolved over time. This helped us understand how VGs influence airflow and impact turbine performance. Installing triangular counter-rotating vortex generators on a DU 91-W2-250 airfoil increased the lift coefficient from 1.16 to 1.56, reduced the drag coefficient from 0.135 to 0.116, and improved the lift-to-drag ratio from 8.6 to 13.4 by re-energizing the boundary layer and delaying separation near stall.

A detailed study on dynamic stall control showed that installing rectangular counter-rotating vortex generators at 15% chord (single-row) on the NREL S809 airfoil delayed the onset of dynamic stall from

13° to 18°, and increased the maximum lift coefficient ($C_{l,max}$) by 40%. Installing rod vortex generators over 3.7% of blade span ($r/R = 0.738-0.775$) on the NREL Phase VI rotor at 10 m/s reduced flow separation, increased local normal and tangential forces by 3.6% and 1.3%, and enhanced overall torque and thrust by 0.54% and 0.67%. Installing delta-shaped vane VGs on a DU97-W-300 airfoil suppressed dynamic stall and reduced lift hysteresis intensity by 72.7% at moderate unsteadiness, while increasing the lift coefficient by 13.2% during the downstroke, confirming improved boundary-layer re-energization and flow attachment. Implementing smart ramp-type vortex generators on a NACA 4415 airfoil and actuating them via shape-memory-alloy control increased $C_{l,max}$ from 1.26 to 1.43, delayed stall angle from 12.5° to 14.3°, and boosted L/D by 42%, while maintaining a negligible drag penalty ($\Delta C_d < 0.1\%$) and consuming only 9.2 W power.

Challenges

Vortex generators cause parasitic drag when air flows smoothly across the blade. This drag reduces blade performance and increases structural loads. Additionally, it affects the blade's aeroelastic response, which might result in instability. Smart VGs energize the boundary layer to reduce stall time. However, they cannot control the blade span lift profile. This control is crucial for advanced control systems, load reduction, and blade pitch variations, especially as the wind changes. Despite its many benefits, vortex generators cannot be used in wind turbine systems until many issues are resolved. The ideal location and size for vertical generators (VGs) vary by turbine and wind to maintain performance under normal flow conditions. Detailed modelling and field evaluation are required. Maintenance and durability are logistical issues that include wet weather, ice, and UV rays can reduce VG efficiency, especially in offshore turbines. Combined aeroelasticity is another growing concern. VGs reduce blade vibrations and fatigue damage by changing the loading. Smart or deployable VGs also face dependability, energy for actuation, and control system issues. Finally, when the increase in annual energy production (AEP) does not include installation, maintenance, or structural integration, many projects' cost-benefit analysis is ambiguous. New concepts in materials science, sensor technology, and real-time aerodynamic modelling are needed to tackle these difficulties.

Emerging Solutions

The utilization of morphing or adaptive vortex generators, capable of adjusting their configuration in real time according to variations in flow, represents a highly promising approach. Shape-memory alloys, piezoelectric materials, and small servomechanisms are commonly utilized for their functionality. This allows for detailed regulation of boundary layer control, simultaneously minimizing ongoing parasitic drag. The function of the VG can be adjusted in real-time to account for variables such as wind speed, turbulence intensity, and blade angle of attack through the integration of AI-driven control algorithms and flow sensors embedded in the blades. At the same time, progress is being achieved in machine learning-based surrogate models and reliable computational fluid dynamics (CFD) techniques to predict the best positioning and effectiveness of VG across diverse operational scenarios. This greatly reduces the need for expensive physical prototypes. Biomimetic designs inspired by bird feathers or sharkskin offer passive control and minimize drag.

Plasma Actuators

A plasma actuator operates using two electrodes, an anode (positive) and a cathode (negative), separated by a dielectric (insulating) material and powered by a high-voltage alternating current, as shown in Figure 20. It uses high-voltage electrodes separated by a dielectric to create a non-thermal plasma that accelerates charged particles, producing an ionic wind (electric wind) along the surface, and it energizes the boundary layer, helping delay flow separation, reduce drag, and increase lift on aerodynamic surfaces. In wind turbines, dielectric barrier discharge (DBD) plasma actuators generate a localized wall-jet that improves the lift-to-drag ratio and mitigates dynamic stall on the blades. Plasma actuators improve VAWT performance by adding momentum to the boundary layer, delaying separation, and weakening dynamic stall during the critical upwind half of rotation. Their benefits

depend strongly on actuation timing, inboard placement, and chordwise position ($\approx 0.3c$). They can significantly increase power output (up to 38%).

This study demonstrates that DBD plasma actuators effectively change the boundary layer and enhance the aerodynamic performance at low Reynolds numbers relevant to small-scale wind turbines. The spanwise double-electrode configuration shows better aerodynamic performance and enables attached flow at a higher angle of attack. Numerical simulations on vertical-axis wind turbines (VAWTs) equipped with plasma actuators show that strategically locating electrodes near the leading edge and optimizing actuation time can increase the turbine's power coefficient by 10-38%. A review demonstrates that plasma actuators may actively reduce dynamic stall and stabilize unsteady flow on wind turbine blades, which leads to more torque and efficiency. Furthermore, it demonstrates that the correct location of electrodes at the leading edge and the right timing of actuation are very important for obtaining a power coefficient boost of up to 38%. A key finding shows that the placement of the actuator and the voltage used have a significant effect on the performance of plasma actuators. In the case of the NACA 0012 airfoil, the actuator was placed close to the leading edge and worked well for flow control. Conversely, for the cambered NACA 4412 airfoil, the optimal actuator placement was found to be approximately at the mid-chord location of approximately 53% of the chord, and these results matched with as illustrated in Figure 21.

In the evaluated cases, the optimal voltages were approximately 18 kV for NACA 0012 and between 21 and 22 kV for NACA 4412. When optimally calibrated, the plasma actuator can augment lift by 13-26% and postpone stall by approximately 2° to 4° . Thus, DBD plasma actuation is a highly promising active flow control technology, but it must be carefully optimized for placement and operating power to maximize its benefits. The DBD plasma actuator generates a near-wall jet that creates momentum in the separated shear layer, thereby delaying separation and weakening the Karman vortex street formed behind the upstream of the cylinder. This study further demonstrates that at a high blowing ratio ($BR = 1.4$), momentum injection significantly reduces vortex shedding, decreases the wake recirculation zone, leading to a 65% drop in vorticity, while at a low blowing ratio ($BR = 0.8$), it shows negligible effects, suggesting that substantial plasma control necessitates a critical momentum input to achieve significant flow alteration.

The simulation results of a Darrieus straight-blade VAWT with plasma actuators at different positions of 10%c, 30%c, 50%c, 70%c, and 90%c on the inner and outer walls of the blades show that using the actuators on the inner edge of the blades independently and activating them during the turbine rotation cycle can improve the torque coefficient and turbine performance. When applying single actuators, the actuators placed in the 10%c and 30%c positions had better results than the 50%c, 70%c, and 90%c

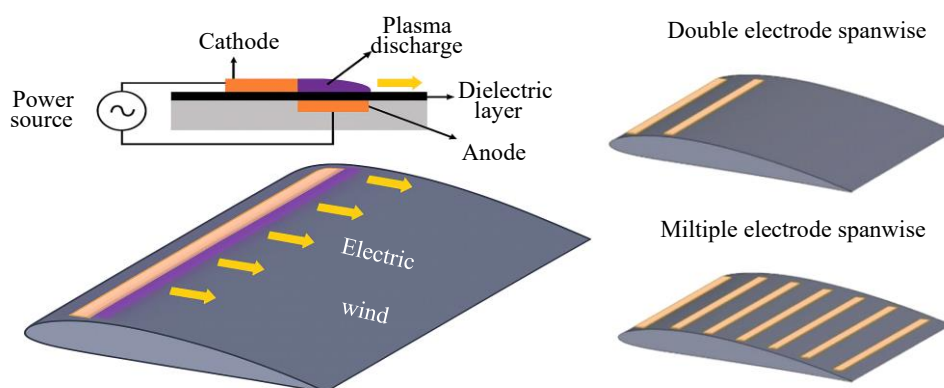


Figure 20. Schematic of the DBD plasma actuator (Left); Schematic design of airfoil with Plasma Actuators (Right).

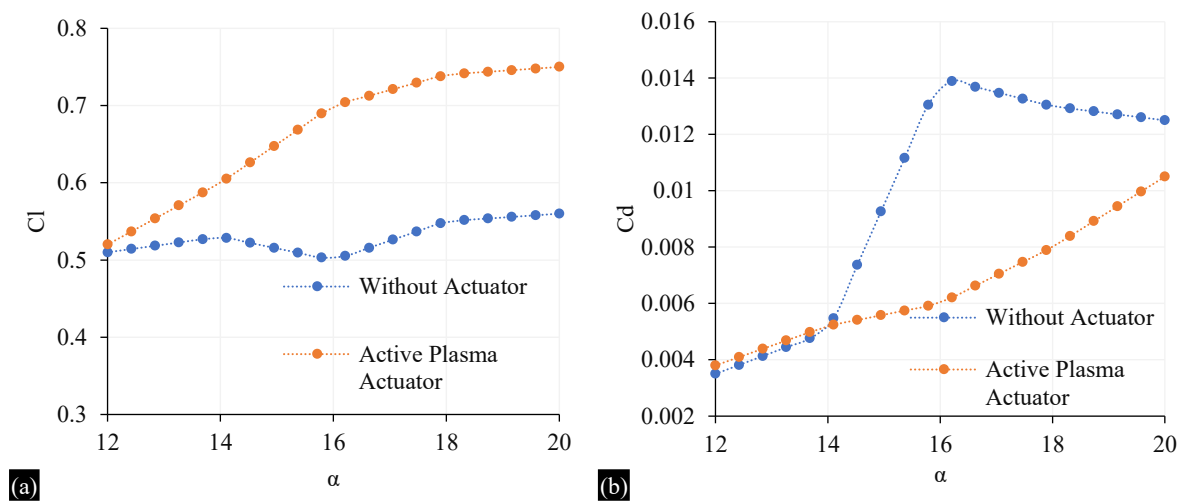


Figure 21. (a) and (b) Comparison of the lift coefficient with and without the plasma actuator at $Re = 158\text{ K}$.

positions. The turbine generating power increased by 29.2% to 90 degrees. Other scenarios were either not cost-effective due to actuator energy usage or did not significantly differ from the 90° case. The influence of plasma actuators at the leading and trailing edges was experimentally carried out, which shows that the actuator at the leading edge controls separation, while at the trailing edge controls lift. The leading-edge separation control increases both C_{Lmax} and α_{stall} , and it results in L/D improvement of 340%, while the trailing-edge actuator at 90% of the chord exhibits a similar effect as a plain trailing-edge flap. Findings from a study, which investigated how the arrangement of plasma actuators influences aerodynamic performance, particularly in terms of lift and drag. Symmetrical actuation means the actuators were placed and operated in a balanced way on both sides of the airfoil or control surface. This configuration led to aerodynamic enhancement, specifically, up to a 67% increase in the lift coefficient and a 63% reduction in the drag coefficient, which quantifies resistance to airflow.

The plasma-actuation-assisted circulation control can improve aerodynamic performance, specifically by enhancing lift. The plasma actuators at the trailing edge led to an increase in the lift coefficient by 0.1, which shows almost similar results compared to. The location of the plasma actuator at 60% chord from the leading edge enhanced the aerodynamic performances of a pitching NACA airfoil. The experimental study of dynamic stall flow control using plasma actuator reported a 7.1% increase in the lift coefficient, a stall delay of 1.3° , a 4.5% reduction in the hysteresis-loop area and a 44.5% decrease in drag coefficient, and the results match with. The influence of a DBD plasma actuator on the performance of a self-pitch VAWT is examined in, which shows an increase of 8% in power coefficient as compared to the base model. Consequently, for a tip speed ratio of $\lambda=1$, the power coefficient is 38% higher than the traditional fixed-pitch VAWT.

Research on nanosecond pulsed plasma actuators shows that these plasma actuators control flow separation primarily through thermal perturbations rather than momentum injection. At low actuation frequencies ($F^+ \leq 2$), large coherent vortices dominate and promote reattachment. At high actuation frequencies ($F^+ > 8$), the actuator acts like an active turbulent trip, accelerating the boundary-layer transition. The intermediate range ($2 < F^+ < 8$) marks a transitional regime between these two mechanisms. The best control effect occurs when the plasma excitation frequency closely matches the natural shear-layer frequency of the baseline. Another study showed that when DBD plasma actuators (on the suction side and trailing edge) were excited at the natural wake-mode frequency ($F^+ = 0.8$), the flow separation was controlled most efficiently. Applying excitation only to the suction-side shear layer ($F^+ = 0.8$) caused the shear layer to break down sooner and the trailing-edge vortices to become weaker. This improved mixing and delayed stall. Research on transverse actuation conclusively demonstrates that a transverse dielectric barrier discharge (DBD) plasma actuator can reduce vortex shedding from a blunt trailing edge by creating a streamwise jet that breaks up the interaction between the shear layers.

This method reduces kinetic energy by up to 60% and 10 dB decrease in the amplitude of shedding frequency, and it shows that it has a lot of potential for reducing aerodynamic noise and drag. Plasma actuation applied to a 1.75 MW wind turbine demonstrated effective suppression of leading-edge separation, resulting in a power increase of 5% when evaluated under actual atmospheric conditions. Deep reinforcement learning (DRL), concentrating on the PPO algorithm, successfully obtained optimal control methods for plasma actuators, achieving a drag reduction of up to 99% and complete suppression of vortex shedding.

Challenges

Plasma actuators are sensitive to the flow regime; they do not have effective functionality at higher Reynolds numbers (more than the order of 10^5). Another problem is that plasma actuators have trouble maintaining a steady electric output when the weather is bad, such as when it rains, snows, hails, or is dusty or when lightning strikes. This leads to significant inquiries regarding their dependability in adverse weather conditions or various environmental situations. Finally, these systems exhibit low energy efficiency owing to significant electrical energy loss as heat during the conversion process, resulting in considerable thermal losses. The efficiency of this conversion process is crucial for increasing their practicality and energy efficiency in real-world applications. Before the implementation of plasma actuators in wind turbines, several significant challenges must be addressed. Controlling the high-voltage requirements of plasma actuators on offshore turbines presents significant challenges.

Emerging Solutions

Key considerations when integrating plasma actuators into wind turbines include environmental durability, power supply and integration, scalability and cost, and performance in high Reynolds number flows. Researchers have focused on developing robust electrode materials and protective coatings designed to enhance the durability of plasma actuators under adverse weather conditions, including rain, snow, dust, and lightning. The objective of these advancements is to ensure consistent plasma discharge performance, regardless of adverse weather conditions. The operational conditions characterized by high speeds and significant Reynolds numbers, frequently observed in wind turbine applications, have consistently posed challenges for plasma actuators. Researchers are currently evaluating innovative actuator designs, including serpentine configurations, that have demonstrated enhanced flow control abilities. Moreover, studies are currently being conducted on adaptive control systems, with a specific emphasis on deep reinforcement learning, aimed at enhancing actuator performance in relation to varying flow conditions.

Blowing-Suction control

Blowing and suction flow control methods have become prevalent to improve the aerodynamic efficiency of modern wind turbines, as shown in Figure 22. To alter the boundary layer behavior and delay or inhibit flow separation, these systems work by injecting or blowing airflow through strategically positioned surface slots on the blade. Blowing and suction help to stabilize aerodynamic loads, improve lift-to-drag ratios, and lessen dynamic stall phenomena in wind turbine applications, particularly in sheared or unstable input situations. Recent advancements, including co-flow jets (CFJs) and dual-suction flow jets (D-SFJs) configurations, demonstrate that coordinated suction on the suction side and blowing near the trailing edge can reduce thrust fluctuations by up to 3% and boost net power output by over 2% in large offshore turbines. Consequently, blowing-suction flow control is becoming more widely acknowledged as a viable aerodynamic enhancement technique for floating offshore wind turbines and next-generation multi-megawatt wind turbines.

The D-SFJ control system showed that the implementation of both blowing and suction mechanisms resulted in a reduction of thrust fluctuations by up to 3%. Similar to the previous study, demonstrates at a wind speed of 11.4 m/s, the Dual-Suction Flow jet (D-SFJ) device efficiently controlled reversed flow to the blade root and mitigated dynamic stall effects brought on by surge motion, reducing the

separation flow area by up to 57%. Even after controlling for micro-pump energy consumption, the D-SFJ device's average net output power improved by 4.82% at 7 m/s and 2.49% at 11.4 m/s respectively, enhancing the performance of floating. During surge motion, the D-SFJ control system demonstrated a 12% increase in average torque and an 8% increase in thrust at a speed of 11.4 m/s, indicating enhanced load regulation and aerodynamic efficiency.

Flow control research on a transonic aerofoil explains that applying low-magnitude suction on the suction side of the RAE2822 airfoil increases aerodynamic efficiency by up to 22.6% at Mach 0.725 and $\alpha = 3^\circ$, outperforming all blowing configurations when power consumption was included. Suction shifted the shock position downstream by 7–10% chord length, reducing the pressure drag component and suppressing separation bubbles, while blowing amplified drag due to boundary layer thickening. Both blowing on the suction and pressure sides led to a net drag increase of up to 20%, with inclusive drag dominated by boundary-layer penalty and pump energy, demonstrating that suction-only control is aerodynamically and energetically superior for transonic flows.

Research on passive blowing study finds that incorporating an inclined contracting slot at the mid-chord of an S809 airfoil leads to up to 130% higher lift, 53% drag reduction, and 372% improvement in glide ratio at moderate to high angles of attack ($\alpha \geq 6^\circ$). Aeroacoustics analysis shows a 14 dB decrease in overall sound pressure level (OASPL) at $\alpha = 17^\circ$, compared to the baseline airfoil.

Analysis similar to that in Section 4.3 shows that coupled blowing and suction indicates that suction delivered through a front-face slot improves wake stability by reducing downwash, decreasing tip vortices, and strengthening base vortices. This can cut drag by as much as 96% and make the flow much more stable. An optimal blowing ratio of approximately 0.5 produces the highest film cooling effectiveness on the suction surface of a rotating turbine blade, as higher blowing ratios cause jet lift-off and reduce surface coverage.

While increasing the blowing ratio enhances jet momentum and weakens inward film deflection, it simultaneously decreases cooling performance owing to film separation. Thus, maintaining a moderate blowing ratio ensures attached, uniform coolant films and maximized cooling efficiency under rotational effects. Experimental and numerical investigations of multi-suction slots (shown in Figure 23) demonstrate that multi-suction jets significantly improve lift performance numerically, with a 480% increase in lift coefficient (C_L) at a stall angle of 22° , as shown in Figure 24, and experimentally, a 55.7% improvement at 16° angle of attack (AOA) compared to the clean airfoil.

The lift-to-drag ratio improved notably, especially at a moderate suction pressure of 200 Pa, confirming the enhanced energy extraction potential of wind turbines. Multiple jets positioned along the upper surface, especially near the trailing edge and maximum thickness region, produced the most favorable aerodynamic performance.

The study on slot-based passive blowing found that, compared with the baseline NREL Phase VI blade, the slotted design increased low-speed shaft torque and power (up to 100%), thrust (up to 20.4%), and flapwise bending moment (up to 26.5%). Annual Energy production (AEP) improved by 21%, demonstrating tangible power generation gains. The slot mechanism was most effective at moderate to

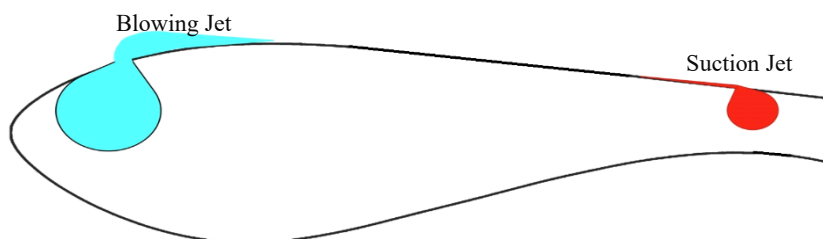


Figure 22. A schematic of a wind turbine aerofoil equipped with blowing-suction control.

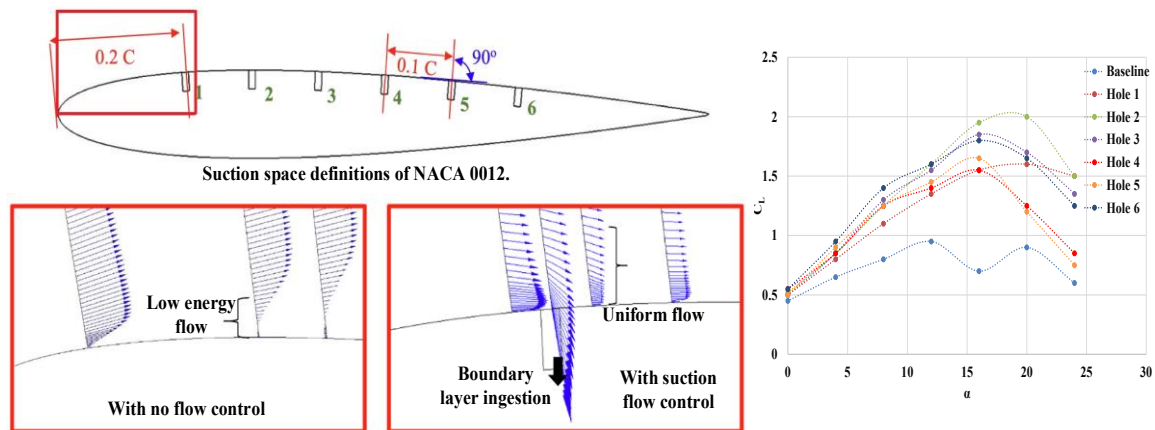


Figure 23. Effect of suction flow on velocity profile for NACA0012.

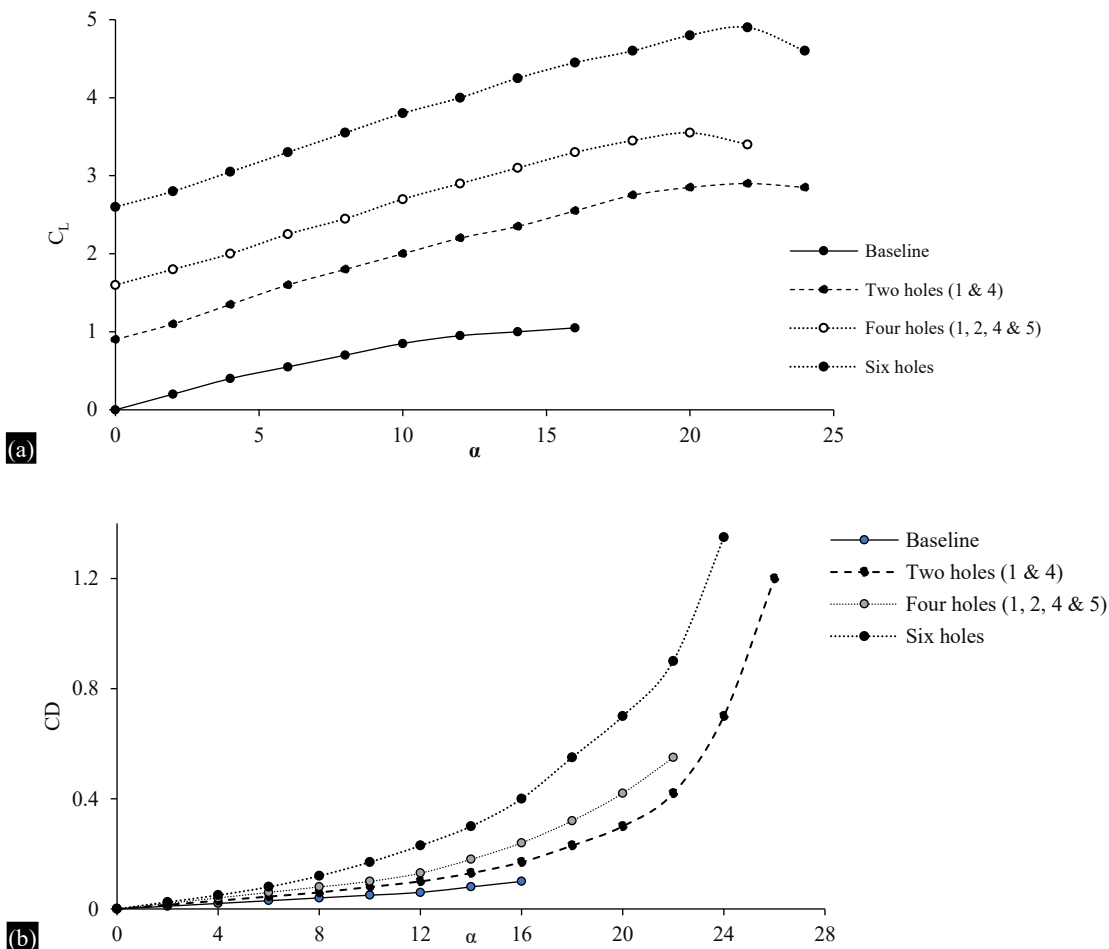


Figure 24. (a) and (b) Aerodynamic characteristics for different configurations of suction.

high wind speeds (≥ 9 m/s). At low speeds (≤ 7 m/s), the performance decreased slightly. A numerical study on the effect of the passive air-blowing on the near-wake region of DU97-W-300 airfoil with blunt trailing edge showed that the optimum configuration, slot width of 4 mm and inlet position at $0.025\%c$, provided the best performance. Although the lift coefficient showed a slight decrease at the critical angle of attack (stall), the drag coefficient was significantly reduced, especially at high angles of attack ($\alpha > 16^\circ$). For a slotted airfoil with slot width $S = 4$ mm and slot inlet location at $0.025\%c$, a maximum C_L/C_d of 35.03 was attained.

A novel method of controlling fluid flow that relies on the combined action of suction and blowing in H-type Darrieus wind turbine explains that blowing-suction synergy (BSS) system substantially improved both aerodynamic efficiency and noise reduction of vertical-axis wind turbines (VAWTs) by synergistically combining leading-edge suction and trailing-edge blowing, yielding a 32.16% increase in power coefficient, 166% rise in lift coefficient, and noise reduction up to 6.56 dB. Additionally, the application of BSS affected the static stall angle, which was delayed by approximately 24°. The impact of blowing and suction jets on the aerodynamic performance of the NACA 0012 airfoil at a moderate Reynolds number of $Re=1 \times 10^5$ was assessed experimentally. The suction jet was situated at 0.3c or 0.6c, and the blowing jet at 0.2c or 0.3c. The blowing jet momentum coefficients ($C_{\mu B}$) of 0.026, 0.104, 0.235, and 0.418 and the suction jet momentum coefficients ($C_{\mu S}$) of 0.007, 0.03, and 0.058 were chosen to be optimized. A single leading-edge blowing jet (0.2c, $C_{\mu B} = 0.104$) enhanced NACA0012 airfoil performance by 18.4% lift gain, 53% drag reduction, and 804% C_L/C_D rise, making it an optimal active flow control method for small-scale wind turbines.

The combined blowing-suction control (blowing at 0.2c and suction at 0.6c) enhances lift by 35%, improves lift-to-drag ratio by 123%, and reduces the cut-in speed by 15% by effectively suppressing flow separation and controlling reattachment, thus boosting small-scale wind turbine efficiency at low wind speeds. A boundary layer suction (BLS) system located at 0.15c and functioning at -40° increases the power output of horizontal axis wind turbines (HAWT) by 225% at a wind speed of 20 m/s and 182% at 13 m/s, respectively. This led to net power gains of 7642 W and 8730 W, respectively. Another study on BLS showed the lowering of Turbulent Boundary Layer-Trailing Edge Noise (TBL-TEN) in NREL 5MW wind turbine by 3.2 dB, as well as raising rotor power by approximately 2%. This work establishes the first realistic 3D application of active boundary-layer suction for aeroacoustics optimization in wind energy systems. In alignment with prior research, the implementation of boundary-layer suction demonstrates a reduction in full-scale wind-turbine trailing-edge noise by 3.6 dB, as well as enhancing rotor power output by 4.75%. Further noise suppression exceeding 5 dB is energetically unfavorable because it increases pump power requirements. Investigation of unsteady blowing actuation on a 2D wind turbine blade demonstrates that it effectively postpones boundary-layer separation and enhances lift under steady flow conditions, while closed-loop control employing surface pressure feedback consistently diminishes unsteady load fluctuations by as much as 12% in turbulent inflow, demonstrating that intelligent actuation synchronized with flow dynamics improves both the aerodynamic stability and fatigue performance of wind turbine blades.

The combined suction-and-oscillatory-blowing (SaOB) system reduces drag by up to 20%, primarily through boundary-layer thinning, enhanced momentum addition, shear-layer excitation, streamwise vortex formation, and thrust generation. The optimal effect occurs when the unsteady jet frequency and strength are balanced with suction flow, confirming that drag reduction scales best with the unsteady momentum coefficient (C_{μ}) and the frequency-quality parameter ($F^+ \kappa^2$) rather than traditional steady momentum measures. Simultaneous injection and suction on the airfoil surface effectively doubles lift (up to 100% increase) and extends the stall angle to 24°, while also reducing drag by up to 127% compared to the baseline (Clark-Y airfoil); these benefits scale directly with the jet momentum coefficient ($C_{\mu} = 0.02-0.16$), and injection proves more influential than suction. Implementing a Co-Flow Jet with a momentum coefficient of 0.12 on the S809 airfoil increases the lift, extends the stall angle by 8.8°, and even generates thrust (negative drag) at angles below 16°, by fully suppressing flow separation. This demonstrates that CFJ is a highly effective active flow control method for improving turbine performance across low- and high-wind conditions.

The Co-Flow Jet system significantly enhances wind-turbine airfoil performance by energizing the boundary flow, delaying stall, and reducing drag to thrust, establishing it as a promising and efficient aerodynamic control technique for next-generation turbine blades. This study explores how active flow control through surface blowing can improve the aerodynamic efficiency of bio-inspired wings with leading-edge tubercles, as illustrated in Figure 25. The authors employed computational fluid dynamics (CFD) using the $k-\omega$ SST turbulence model to simulate steady, tangential surface blowing at various

chordwise locations ($0.3c$ to $0.8c$) and blowing velocity ratios ($R = 0.5, 1$, and 2) on a NACA63(4)-021 airfoil featuring sinusoidal tubercles of amplitude $0.12c$ and wavelength $0.25c$ with Reynolds number 2.05×10^6 and a free-stream velocity of 30 m/s. Results shown in Figure 26.(b) indicate that a blowing velocity ratio of 2 applied at $0.3c$ yielded the most significant improvement, enhancing lift by approximately 28% and increasing aerodynamic efficiency by 25 – 50% without additional drag penalty.

Challenges

Blowing-suction devices have aerodynamic benefits, including better lift and a delay in stalling; however, they are difficult to use in real life because of their complicated design and engineering problems. A complete redesign of the blade is essential to fit the actuation system, which includes pumps, valves, and control electronics, while considering performance, weight, cost, and structural integrity. Incorporating a blowing and suction slot could affect the mechanical strength of the blade. Ice, dust, or moisture can obstruct the openings with relative ease. These obstructions could lead to vibrations and unexpected loads if the flow regulation system fails to operate effectively. The placement of quick-response valves in proximity to the surface of the blade presents challenges for accessing them during repair and maintenance activities. Positioning these devices on elevated, remote wind turbines may expose sensitive electrical components to the danger of lightning strikes.

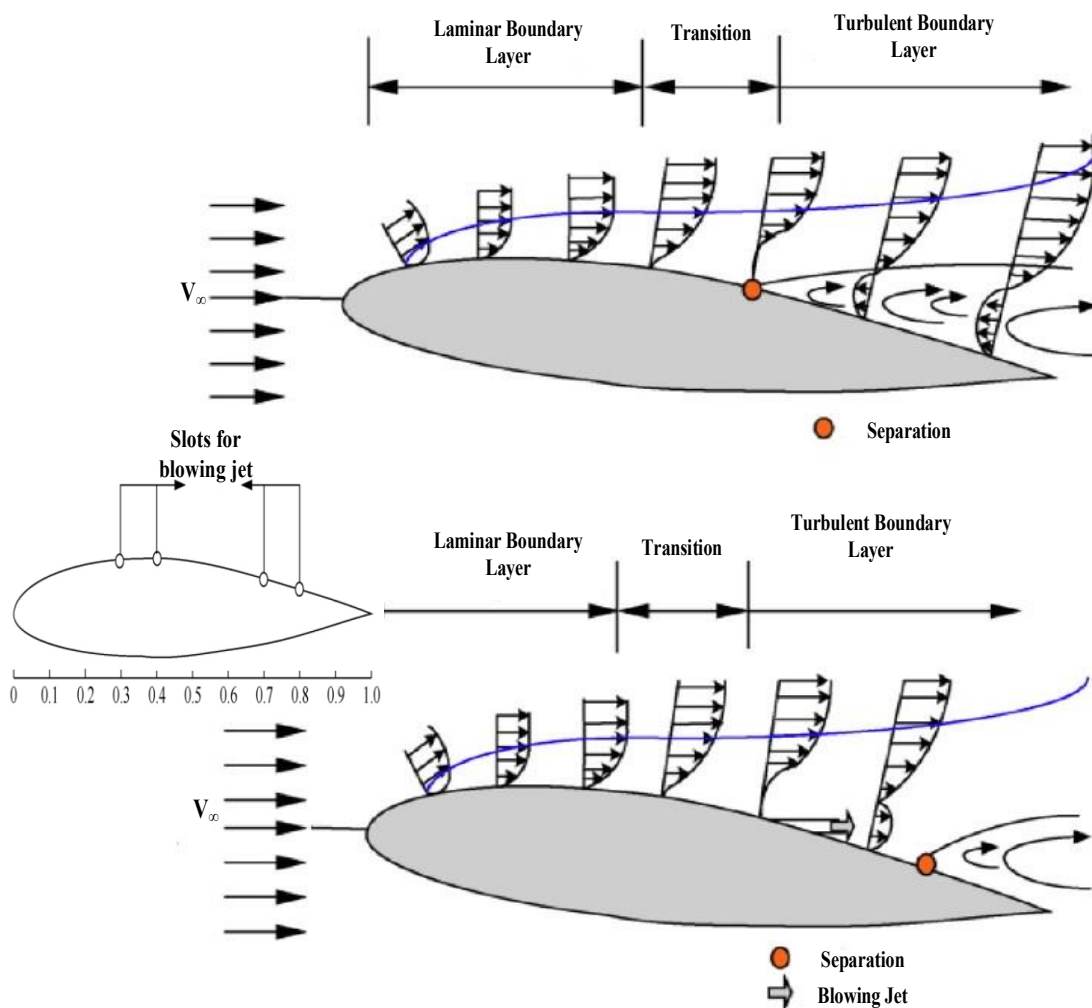


Figure 25. Schematic of velocity profile over airfoil without /with blowing.

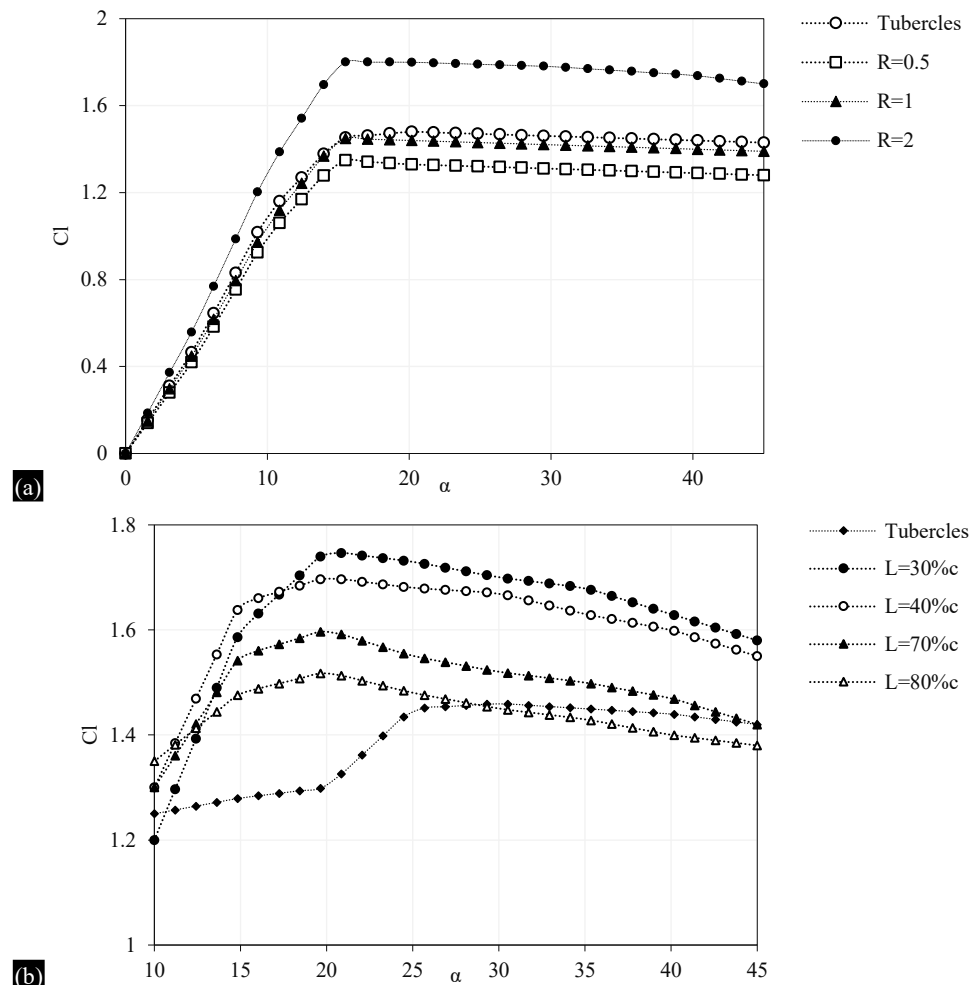


Figure 26. (a). Lift coefficient at various angles of attack with different blowing velocity ratios (R). (b). Lift coefficient for various angles of attack at different blowing locations ($R=2$).

The complexities involved in directing pressurized air significantly complicate the setup process. This indicates that it is necessary to utilize hub-based compressors or pumps along with tubing at the points where revolving blade joints are present. Designing, maintaining, and preserving these components present significant challenges because they must function effectively under substantial loads and continuous movement. Ultimately, the utilization of compressed air jets generates increased noise levels, particularly when they engage with the surrounding airflow. This may complicate adherence to regulations and safeguarding the environment.

Emerging Solutions

In solving the engineering challenges associated with integrating blowing-suction systems into wind turbines, researchers have explored various innovative technologies. The use of shape memory alloys and piezoelectric actuators is a promising approach. The utilization of these materials allows for the regulation of flow within a designated area, thereby eliminating the necessity for complex mechanical systems. Employing surface morphing or self-actuating apertures may eliminate the necessity for integrated pumps and valves. The implementation of distributed micro-blowers or solid-state plasma actuators represents an innovative approach. These devices facilitate airflow through a mechanism that eliminates the need for moving components, thereby reducing maintenance requirements and minimizing the potential for issues related to lightning. Furthermore, advancements in additive manufacturing enable the direct incorporation of intricate internal channels and structures into the blade during the production process. This enhances the protection of the slot and minimizes structural

deterioration. To ensure that the operational slot remains functional, self-cleaning coatings and electrothermal de-icing devices are being implemented. This addresses environmental issues such as the accumulation of ice or dust. The implementation of wireless power transmission and battery systems onboard could potentially reduce the need for routing electricity through rotating joints at the system level. The integration of data-driven adaptive control algorithms with artificial intelligence-driven predictive maintenance is underway to enhance safety, reduce operating costs, and facilitate real-time optimization of flow control actuation. The objective of these enhancements is to bridge the divide between structural integrity and aerodynamic efficiency. This will enable the development of advanced and adaptable designs for wind turbine blades.

Leading-edge Protuberances (LEP) and Trailing edge serrations (TES)

Leading-edge protuberances (LEPs), often called tubercles after the humpback whale-inspired geometry, are sinusoidal or rounded bumps placed along the leading edge of lifting surfaces and act as passive flow-control devices that modify the boundary-layer and separation behavior. Experimentally and numerically, LEPs have been shown to generate spanwise-localized streamwise vortices and to compartmentalize the pressure field across the chord, which together energize the suction-side boundary layer and delay or moderate stall; the net result is a broadened operating envelope with delayed stall and improved post-stall lift behavior in many cases. The experimental demonstration and parametric study by show that sinusoidal leading-edge protuberances (tubercles) on a two-dimensional NACA 634-021 airfoil significantly alter stall behavior, enhance post-stall lift, and maintain attached flow at high angles of attack, primarily due to localized flow separation control induced by the geometry of the protuberances. Above the baseline stall angle (19° – 21°), airfoils with protuberances achieved up to 50% higher lift with little or no additional drag penalty. The largest amplitude (0.12c) foils exhibited near-constant lift between 10° – 26° , effectively eliminating abrupt stall, as illustrated in Figure 23. The amplitude of the protuberances was the dominant factor influencing performance, whereas the wavelength had minimal effects.

Incorporating leading-edge protuberance (LEP) blades into a vertical axis wind turbine (VAWT) makes the structure much more stable by passively managing vibrations through better aerodynamic damping effects. Compared to regular straight blades, the LEP-modified blades cut bidirectional vibration by up to 70% and boosted aerodynamic damping, especially at medium to high wind speeds (11–20 m/s). This reduced dynamic stall effects and stopped unstable aerodynamic loads. Wind turbine blade lift coefficient (C_L) and stall-delay behavior are greatly improved by leading-edge protuberances (LEP), which are modelled after humpback whale flippers. This is particularly for the turbulence intensity of 0.5–4.92%. Compared to straight leading-edge blades, LEP blades produce higher turbulence intensities, resulting in more lift and smoother stall characteristics, indicating superior aerodynamic stability. Among the tested geometries of small, medium, and high LEP, the high-amplitude LEP configuration showed the best aerodynamic performance, achieving higher maximum lift and smoother stall transition, as shown in Figure 27. Leading-edge tubercles regulate the stall process, enhance post-stall lift, and stabilize flow by generating localized vortices. Normalizing aerodynamic coefficients by the valley chord length provides consistent scaling and confirms that tubercles act like a series of delta wings, improving lift through vortex-induced flow control. Integrating leading-edge tubercles into hybrid VAWT blades increases the power coefficient up to 0.475 at $TSR = 3$, achieving superior energy capture across both low and high TSRs compared to conventional and non-tubercled hybrids. The design ensures positive static torque ($C_{ts} = 0.319$) at all azimuths, enabling self-starting capability and efficient low-speed operation, making it ideal for small- to large-scale wind applications.

A detailed review of bio-inspired tubercles explains that leading-edge tubercles delay flow separation and stall onset, enabling smoother aerodynamic performance and sustained lift in the post-stall regime. At low wind speeds, smaller amplitudes and shorter wavelength tubercles enhance lift and reduce drag, while larger amplitude and wavelength perform better at higher speeds. Adding sinusoidal leading-edge

protuberances to the H-Darrieus vertical axis wind turbine made it much easier to start up on its own. This lowered the cut-in wind speed from 7 m/s to 5.5 m/s and shortened the time it took to start up. The turbine showed a maximum C_p that was 20% to 34% higher at higher wind speeds (up to 9 m/s), showing that the tubercled blades are aerodynamically superior. The incorporation of sinusoidal leading-edge serrations on an H-type VAWT suppressed dynamic stall at azimuth angles of 90° to 150° , generating counter-rotating vortex pairs that delayed flow separation and enhanced lift. This created counter-rotating vortex pairs that delayed flow separation and increased lift. This change made the power coefficient go up by 18.7% at tip speed ratio of 2, and the lift coefficient go up from 1.7 to 1.95. Also, at low wind speeds, the serrated design produced 50% more power than the baseline, showing that it is very good at controlling stalls and improving efficiency in low-Reynolds-number conditions.

A comprehensive analysis of the leading-edge protrusion indicates that the spherical leading-edge protrusion (SLEP) postpones flow separation and enhances post-stall lift performance, yielding an 8.2% improvement in power coefficient relative to the baseline model. In contrast, the triangular leading-edge protrusion (TLEP) degraded aerodynamic efficiency, confirming SLEP as the most effective passive flow control for low-Reynolds-number wind turbine blades.

Trailing-edge serrations (TES) are passive flow control features, typically sawtooth or wavy modulations (shown in Figure 24), added to the blade trailing edge to primarily reduce turbulent boundary-layer trailing-edge (TBL-TE) noise in wind turbine blades. The underlying

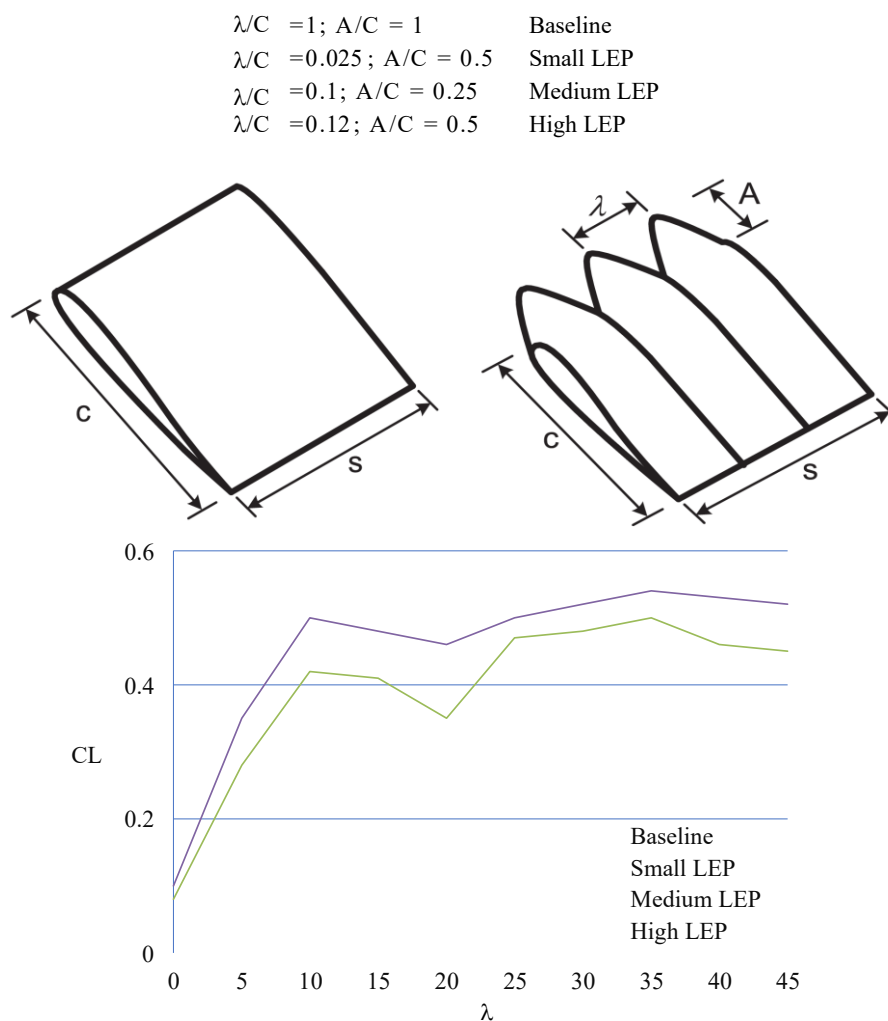


Figure 27. Nomenclature of the baseline straight leading-edge model and the modified leading-edge protuberance model and their corresponding characteristics of lift.

The mechanism is that serrations disrupt the spanwise coherence of wall-pressure fluctuations convecting towards the trailing edge, inducing phase interference that reduces the efficiency of acoustic radiation, and sound reduction is reported to be up to approximately 7 dB. A study on trailing-edge serrations effect on wind turbine performance reported that the serrations increased the lift coefficient (C_l) across all tested airfoils (Nordex ADO30 airfoil and NACA64₃418 airfoil) up to 20% and a negligible drag penalty, improving the C_l/C_d ratio and maintaining the stall angle unchanged. Wind turbine simulations and field data showed 1–1.5% higher electrical power output and an annual energy production (AEP) gain of 9%. A detailed study on the aerodynamic performance of different trailing edge serrations showed that sinusoidal serrations provided the best aerodynamic performance, achieving a 6.8% higher maximum lift coefficient, 10.6% lower drag, and 2° stall angle delay, leading to a 19.5% improvement in L/D ratio at 17° angle of attack. Square serrations with a smaller wavelength-to-amplitude ratio ($\lambda/h = 0.6$) showed 1.2% higher aerodynamic performance, while triangular serrations experienced early flow separation and degraded performance.

Figure 28 shows (a) an owl in flight, (b) a close-up view of an owl wing with trailing-edge serrations, and (c) the parameters for serrations. Research on bio-inspired trailing edge serrations reveals that bionic serrated trailing edges, modelled after owl wings, can significantly diminish aerodynamic noise by as much as 7.5 dB, while enhancing the lift-to-drag ratio by 11.2% in comparison to a standard flat edge. The serrations contribute to improved vortex mixing and boundary layer reattachment, which in turn reduces pressure fluctuations and results in a quieter, more aerodynamically efficient airfoil design. The study of wake characteristics concludes that trailing-edge serrations on the S809 airfoil effectively suppress wake intensity and dynamic pressure fluctuations compared to extended flat plates. While the extended flat plate (EFP) increased wake intensity and instability, TES suppressed wake turbulence and reduced wake intensity, especially in post-stall conditions. The serration angle also influences noise reduction in wind turbine blades.

The effect of serration angle on the NACA6512-63 airfoil was found to be $\lambda/h = 0.3$ is the ideal serration angle for noise reduction, resulting in the best low-frequency ($St < 2.5$) noise suppression and the most effective linearly distributed multipole pressure pattern. A moderate serration angle optimally balances flow stability and acoustic attenuation, as $\lambda/h = 0.6$ produced significant outward flow and turbulence misalignment, which reduced the destructive interference effect, while $\lambda/h = 0.15$ exhibited minimal low-frequency benefit.

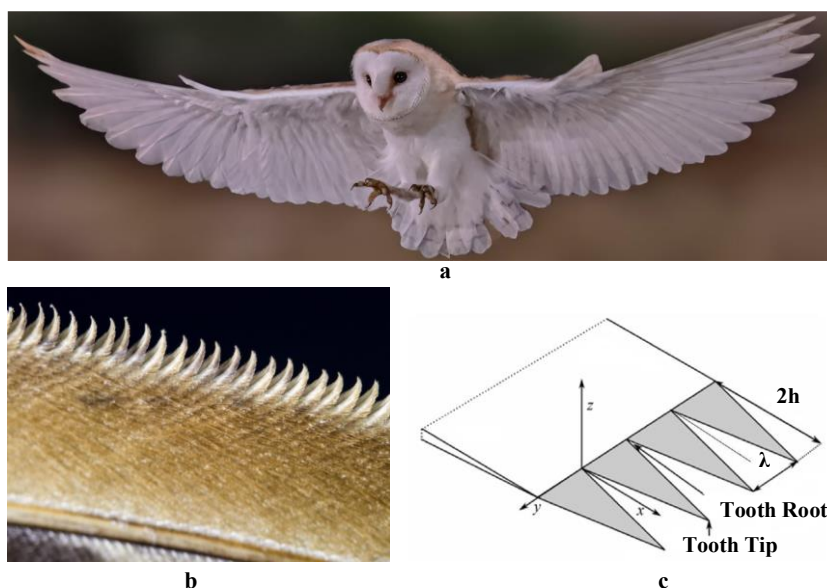


Figure 28. (a) Owl during flight (b) Closeup view of Owl wing with trailing edge serrations (c) Parameters for serrations.

Similar to results from, another bionic trailing edge serration inspired by owl wings effectively reduces aerodynamic noise by up to 5.47 dB and improves lift-to-drag ratio by 11.5%, compared to the baseline airfoil. This improvement results from enhanced vortex dissipation and weakened wall-pressure fluctuations, making the serration design ideal for low-noise, high-efficiency wind turbine and aircraft applications. Research on rounded trailing-edge serrations explains that it has the best aerodynamic efficiency, achieving a 15 % higher lift-to-drag ratio, compared to the baseline, by delaying flow separation and reducing drag; while sharp-edged serrations increase lift at mid angles but cause higher drag and earlier stall. The study experimentally evaluates a NACA 0020 airfoil with extended trailing edges under varying turbulence intensities (0.3%-12%), shows that the extended trailing edge modification effectively delays stall and sustains aerodynamic performance under moderate turbulence, marking it as a robust passive control mechanism for maintaining lift and stability in unsteady flow. These results align with the use extended flat plate (EFP) trailing edge S809 wind turbine blade, which explains that a 10% chord-length extended flat plate (EFP = 0.1C) delivers the best aerodynamic and downstream performance, reducing wake strength and velocity deficit up to a turbulence intensity of 10%. Larger extensions (0.2C, 0.3C) increase turbulence by approximately 12%, making 0.1C the optimal configuration for stable, efficient flow in wind farm conditions.

Challenges

Many wind-tunnel and 2D airfoil tests show stall delay and improved post-stall lift, but the results vary strongly with protuberance amplitude, wavelength, spanwise extent, and Reynolds number; therefore, lab gains do not always carry to full-scale rotating blades. Certain tubercle geometries can worsen energy capture in typical operating environments by increasing drag or decreasing L/D at low angles of attack. Adding sinusoidal geometry to large composite blades complicates molds, inspection, repairs, and can change stress concentrations or icing/erosion susceptibility at the leading edge. Field deployment and maintenance logistics remain unresolved at the utility scale. The amount of surface that is exposed to wind, rain, or debris and the way air pushes on the surface (local loading) are both impacted when engineers alter or reshape the leading edge of an aircraft wing or turbine blade. Modifying the leading edge helps aerodynamics, but the long-term durability and cost effects are still uncertain.

Increased aerodynamic load variations, structural degradation, and unclear performance under three-dimensional turbulent flow are some of the problems associated with trailing-edge serrations, despite their ability to reduce turbine noise. A recent study confirmed that optimization, durability, and erosion issues remain major obstacles for reliable long-term deployment. The study found that wavy leading edges (WLEs) can reduce trailing-edge noise by up to 33.9 dB, mainly by disturbing coherent vortex shedding. The wavy leading edges depend heavily on wave shape and angle; however, their actual 3D performance and the balance between noise reduction and aerodynamic efficiency remain uncertain.

Emerging Solutions

Recent CFD and experimental work show the best trade-offs when tubercles are optimized (height, wavelength, and attenuation) and applied only to the outboard, rather than full-span blunt modification. This reduces drag penalties while maintaining stall-control benefits. Deployable or adaptive small-scale protuberances (or morphing skins) that appear only during stall/gust events can provide benefits without permanent drag penalties; morphing research is actively growing. Combined 3D RANS/LES, adjoint, and surrogate optimization for tubercle geometry are being used to predict full-scale rotating performance rather than extrapolating 2D tunnel data. These workflows help reduce unexpected scaling losses. Small-scale field tests (and manufacturer trials) focused on partial-span or modular retrofits help evaluate real wake, noise, and farm-level effects before fleet adoption. New serration profiles (curved, combed, and saw-tooth variants) are tuned to reduce aerodynamic penalties while maintaining noise attenuation across a wider frequency band. Experimental and CFD studies show promising improved L/D retention. Applying serrations only in blade sections where turbulent boundary layer and noise production are highest (outer spans, specific spanwise regions) reduces aerodynamic losses while preserving noise benefits. Combining serrations with porous trailing edges, flexible tips, or active flow control (mini-actuators, plasma, micro-flaps) can suppress noise with lower drag penalties; these hybrid approaches are under active research.

Boundary Layer Fence

Boundary-layer fences (also called wing/stall fences or spanwise fences) are passive spanwise devices mounted on blades to inhibit spanwise crossflow, control three-dimensional separation, and confine vortical structures, thereby delaying or moderating stall and reducing secondary-flow losses that degrade rotor performance. A study on fences on horizontal wind turbine blades explains that using multiple supercritical airfoils (FX66-S-196V1, FX63-137S, SG6043) along the blade radius optimizes lift-to-drag distribution and increases the power coefficient by approximately 8% compared to a single-airfoil blade (NACA4412). Installing fences at specific radial positions further enhances performance by reducing spanwise flow and induced drag, yielding an additional 16% improvement in power coefficient and complete flutter suppression.

The installation of a chordwise fence on tapered wings effectively delays stall and enhances lift by suppressing spanwise flow from the tip to the root, reducing tip vortex interaction, as illustrated in Figures 29 and 30. The best aerodynamic improvement occurs for the least tapered wing, showing a lift increase up to 13.2% and stall delay of 5° , while fences also improve lift by 5-7% for higher taper ratios through better boundary layer control and flow attachment. A comparative study of active flow control (AFC) using a wall-normal slot jet and passive boundary layer fence (BLF) shows AFC increased CL , max by 10.6–23.4%, compared to 10.2–19.3% for BLF.

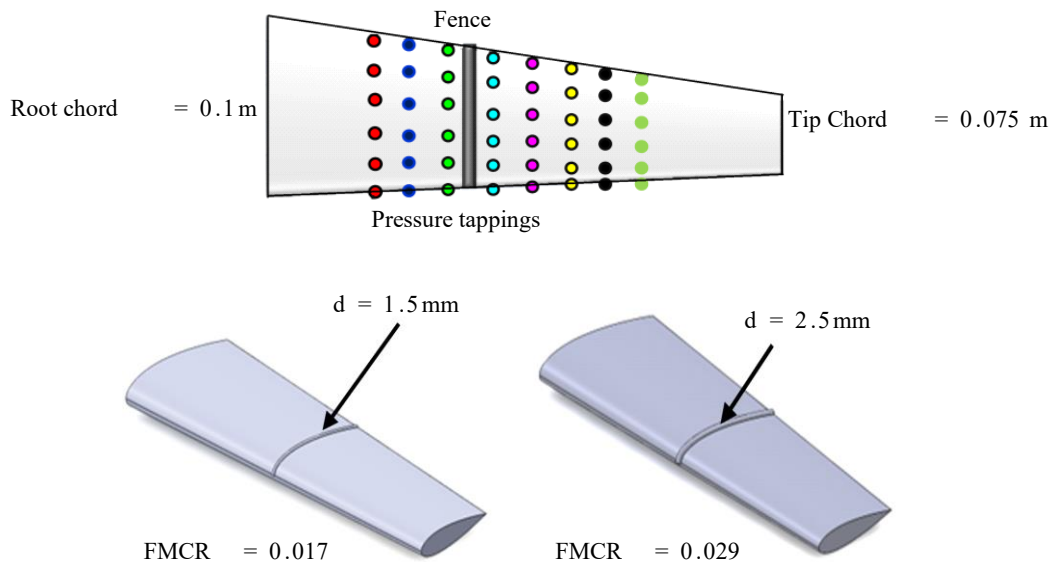


Figure 29. NACA 63(4)-021 with boundary layer fences having two fences mean chord ratios (FMCR)

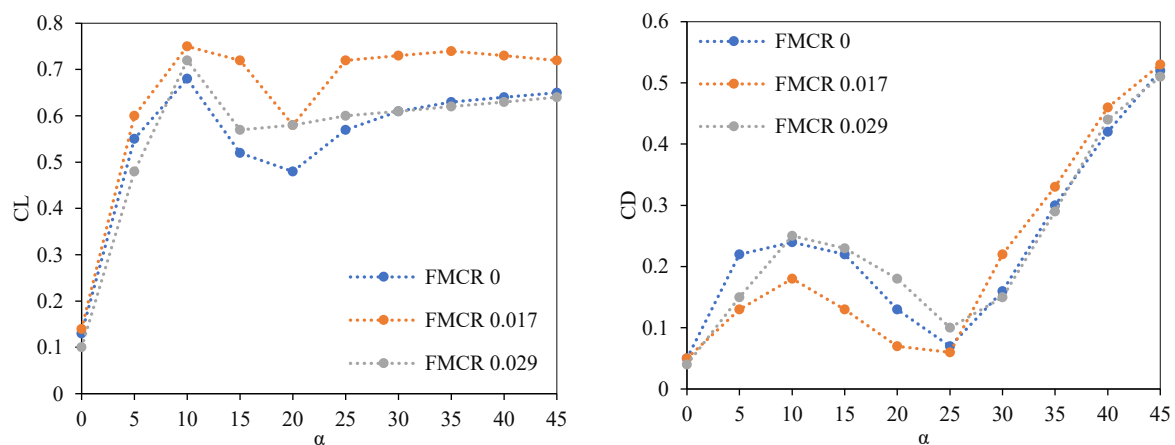


Figure 30. Variation of the coefficient of lift.

The stall angle was delayed up to 23° beyond the baseline for the AFC and 19° for the BLF. Similar to this result, another study concluded that combining a high swept angle (45°) with an anhedral angle (15°) at the blade tip significantly improves turbine efficiency. This configuration enhanced the power coefficient (C_{pmax}) by up to 137% by generating strong roll-up vortices, reducing tip losses, and stabilizing airflow along the blade span.

A study revealed that endwall fences designed with strategic shapes, particularly those featuring nonuniform height profiles, serve as a straightforward, passive, and aerodynamically effective method for diminishing separation in high-lift turbine rotors. This enhances their efficiency while eliminating the necessity for complex actuation systems. In Horizontal Axis Wind turbine, adding boundary layer fences to the blades substantially improves aerodynamic efficiency and power generation, further showing that the installation of fences resulted in up to 11.8% increase in power output compared to the baseline rotor. Research on partially stepped geometries (fence-like) on a NACA0012 airfoil demonstrates that these stepped geometries modify the surface pressure distribution and flow topology, producing step-flow structures (recirculation zones, reattachment lines, and corner eddies) that enhance lift and delay stall, especially when the step is located on the pressure side.

Challenges

Fences block spanwise flow but create pressure/viscous losses that can increase profile drag in attached flow, thereby reducing efficiency at design conditions (critical for HAWTs where low-angle, high-efficiency operation dominates). Fences generate secondary vortices and recirculation, which, if poorly sized or placed, can reduce lift locally or shift load distributions unfavorably. Fence effectiveness measured on small models or 2-D sections often does not scale linearly to full blades; vortex strength and boundary-layer receptivity change with Reynolds number and surface roughness. On rotating HAWT blades and VAWTs, Coriolis and centrifugal forces change boundary-layer behavior and tip vortex dynamics, potentially altering fence performance compared with static tests. Fence roots and attachments can create stress risers and fatigue hotspots under cyclic loading, especially on flexible turbine blades. Even low-mass fences increase blade inertia and may affect dynamic response, particularly for large utility blades where mass penalties are tightly budgeted. Fences must withstand centrifugal forces, erosion, and bird/icing strikes without detaching. Leading-edge impacts, sand/ice accretion, and insect adhesion degrade the sharpness/shape of fences, reducing effectiveness over service life. In cold climates, fences can change local flow paths that promote ice accumulation or make de-icing less effective. Retrofitting fences to existing blades complicates inspection routes and repair logistics. Fences produce extra vortical structures and shedding that can increase tonal or broadband noise, important for onshore turbines and aircraft. Performance is highly geometry-sensitive (height, chordwise position, span coverage). Few industry standards exist for fence sizing on blades. Most studies use static or 2-D tests; fewer high-Re rotating experiments or full-scale field trials exist.

Emerging Solutions

Recent research toward improving the effectiveness and practicality of boundary layer fences (BLF) in wind turbine and aerospace applications has focused on adaptive geometry, hybrid flow-control integration, and material durability advancements. Hybrid approaches combine BLF with vortex generators, leading-edge tubercles, or trailing-edge serrations. This creates synergistic effects, as fences limit spanwise flow while other devices improve the boundary layer or spread tip vortices. According to the existing literature, the investigation into deployable or morphing fences is currently underway, utilizing shape-memory alloys and load-responsive flexible structures for the management of stall control. Recent advancements in surface coating, anti-erosion materials, and hydrophobic/anti-icing treatments enhance operational longevity in challenging environments, tackling a significant durability concern in practical applications. Finally, advancements in high-fidelity rotating-blade large eddy simulations, aeroacoustics solvers, and reduced-order vortex models are enabling precise predictions of boundary layer flow behavior in real-world scenarios, considering both atmospheric and rotational influences. These advancements make boundary layer fences an excellent option for a lightweight, energy-efficient method of passively or semi-actively controlling flow to prevent wind turbine blades from stalling, lessen fatigue, and increase their stability in the wind.

DISCUSSIONS

Prospects

This literature analysis on flow-control systems highlights the substantial potential for improving the overall efficiency and aerodynamic performance of wind turbines. Flaps, such as active trailing-edge devices, adaptive morphing flaps, and trailing-edge flaps, remain among the most effective flow-control mechanisms for wind turbine blades. Under unstable loads, gusts, and yaw misalignment, they offer reliable methods to modify lift/drag characteristics and camber. Similar to flaps, microtabs provide efficient load management without a significant drag penalty. Additionally, microtabs can be incorporated as arrays or modules to achieve global aerodynamic effects because of their tiny size and low inertia, which enable quick deployment and control at minimal actuation power. The next generation of miniature trailing-edge devices will focus on morphing or adaptive surfaces that can dynamically modify local camber or circulation without creating geometric discontinuities. Vortex generators remain a well-known passive technique for delaying separation by energizing the boundary layer via streamwise vortices. The prospects now revolve around smart VGs (deployable or retractable vanes), micro-vortex generators (MVGs), and hybrid VG arrays that respond to inflow conditions.

A recent study on passive boundary-layer separation control found that VGs remain beneficial for large wind turbines. Plasma actuators represent a more cutting-edge active flow control technique, where dielectric-barrier discharge (DBD) or other plasma systems inject momentum (zero net mass flux) into the boundary layer, delay separation, or suppress stall. Future trends for plasma actuators in wind turbines include scaling from model-scale to full-scale blades, integration in offshore harsh environments (e.g., rain, salt, icing), and fusion with machine-learning/AI-optimized control schedules (burst-mode, pulsed actuation). A recent review outlines these prospects for plasma actuators. Blowing (injecting momentum) and suction (removing low-momentum fluid) are active fluidic control strategies for boundary-layer and separation control. Their outlook in wind turbines is strong for dynamic stall mitigation, power coefficient improvement under off-design conditions, and noise reduction.

The future of LEP/TES lies in bio-inspired leading-edge morphing, adaptive slats for variable wind conditions, and smart trailing-edge devices built into massive offshore turbine blades. Additionally, coupling LEP/TES with sensors and actuation to switch between passive/active modes will enhance load alleviation and lifetime. Boundary Layer Fences (BLFs) are typically passive control, installed spanwise on the blade surface to inhibit spanwise flow or separate vortex structures. Future trends include deployable fences that adjust height/angle, micro-fence arrays for large blades, and integration with active actuation (e.g., small jets at fence edges) for localized load control and stall suppression.

Figure 31 shows the lift enhancement of various flow-control devices, specifically in terms of how well they enhance lift, measured by the change in maximum lift coefficient ($\Delta C_{L, \max}$). The change in maximum lift coefficient ($\Delta C_{L, \max}$) quantifies how much peak lift a surface (such as a wing or blade) can generate due to a modification, such as adding a flow-control device ($\Delta C_{L, \max} = \Delta C_{L, \max, \text{with device}} - \Delta C_{L, \max, \text{baseline}}$). The data come from studies focused on wind turbines and summarize how different technologies perform. Among the investigated techniques, microtabs and leading-edge protuberances demonstrated the highest lift augmentation, followed by conventional flaps and blowing/suction systems, which also exhibited consistent aerodynamic benefits. In contrast, trailing-edge serrations and boundary-layer fences only slightly improved the lift. In general, the comparison results show that using smart, adaptive flow-control technology is a good way to improve lift generation and aerodynamic efficiency in the next generation of wind-turbine blades. Figure 32 shows the technology readiness level (TRL) of the flow control devices reviewed. The evaluation of technology readiness levels (TRL) examines the development stage of different methods for flow control and aerodynamic improvement. Conventional flap systems (rigid/ATEG) and Gurney flaps exhibited the highest level of readiness, achieving a TRL of 9, which signifies complete commercialization and operational implementation in aviation applications. In a similar vein, vortex generators and trailing-edge serrations demonstrated advanced maturity, having successfully navigated all stages of development to reach pre-production and commercial applications.

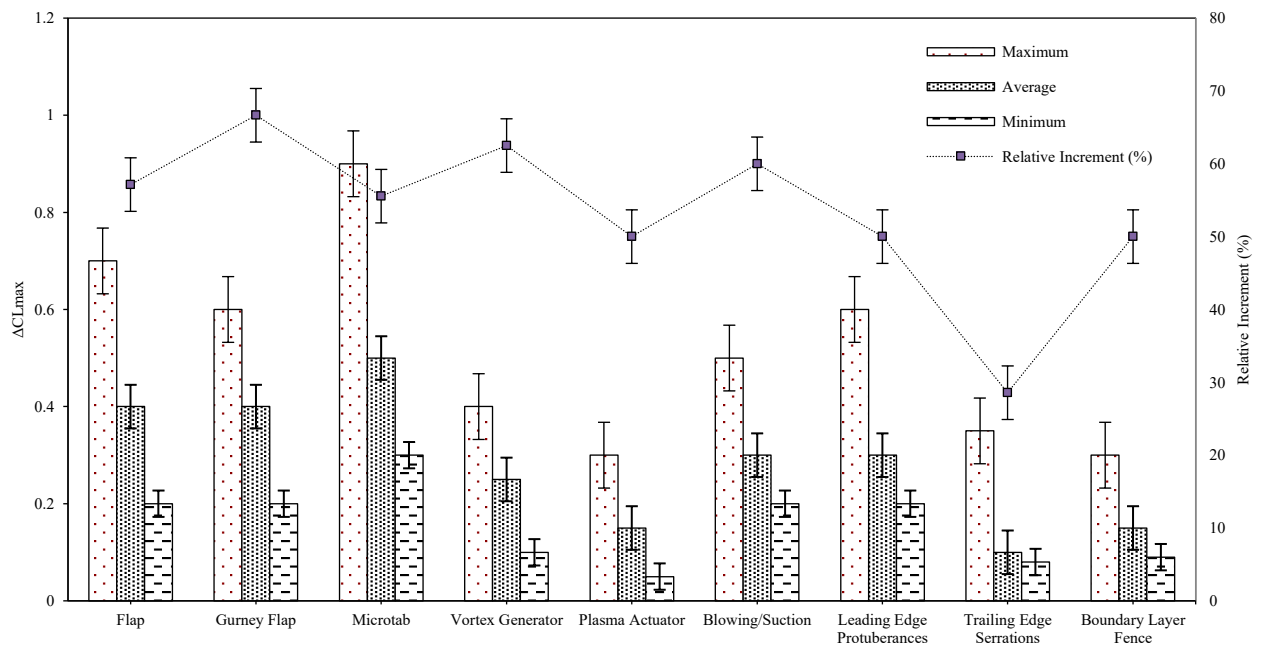


Figure 31. Lift Enhancements of reviewed flow control devices.

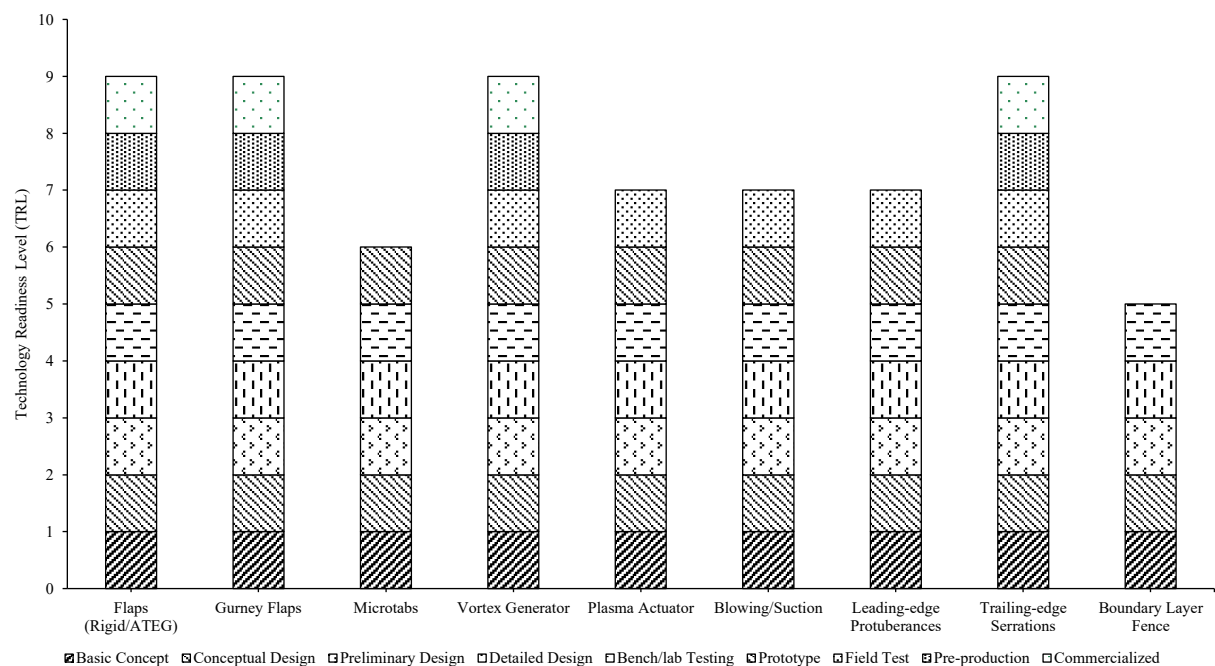
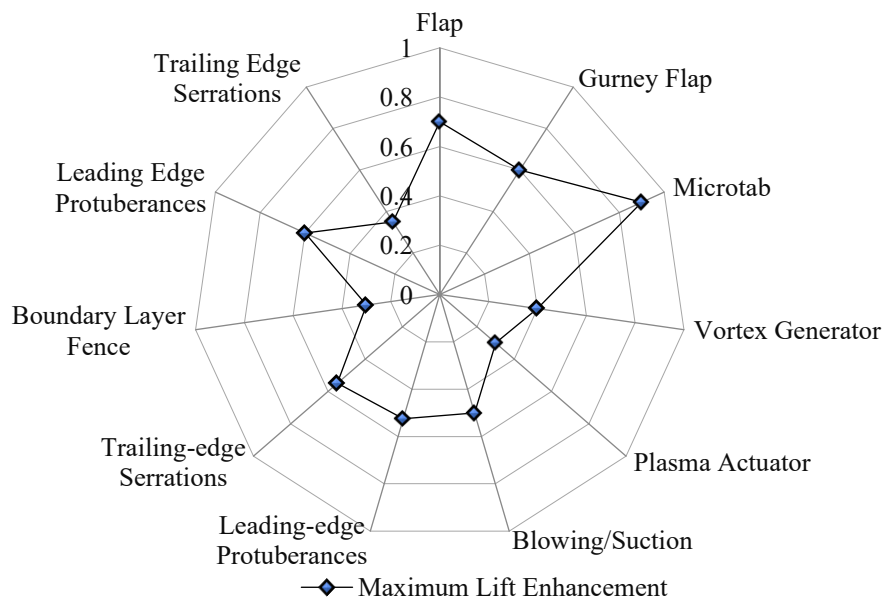


Figure 32. Technology readiness level (TRL) of reviewed flow control devices.

Conversely, microtabs and boundary layer fences are currently positioned at lower readiness levels (TRL 5–6), with their validation largely achieved through prototype development and laboratory testing. Technologies such as plasma actuators, blowing/suction systems, and leading-edge protuberances have reached a level of maturity where they have been successfully validated in operational settings, although their large-scale application remains limited. This comparative analysis (Table 3) highlights that although traditional passive flow control devices have reached full maturity, active flow control methods are still advancing towards practical implementation in aerospace systems.

Table 3. Summary of prospects.

Technique	Maturity	Best future prospects
Flaps	High	Development of smart morphing trailing-edge flaps using piezoelectric or shape-memory materials.
Microtabs	Moderate	Implementation of MEMS (Micro Electromechanical System)-based microtab arrays with high-frequency actuation and distributed spanwise control.
Vortex Generators	High (passive)	Active or deployable vortex generators that adapt to flow conditions; Machine-learning-optimized VG placement.
Plasma Actuators	Emerging (active)	Transition from lab to full-scale DBD implementation on large blades.
Blowing & Suction	Emerging (active)	Deployment of sensor-triggered, miniature pulsed jet and suction systems.
LEP/TES	Moderate	Development of bio-inspired morphing edges.
BLF	Lower (passive)	Development of deployable and retractable micro-fence arrays for localized separation suppression

**Figure 33.** Maximum lift enhancement of the reviewed flow control devices.

Future Works

This review reveals the following future research directions:

- Most active flow control methods (especially plasma actuators, boundary layer fences, microtabs, and blowing-suction systems) remain at medium TRLs. Large-scale field experiments under realistic atmospheric turbulence, yaw misalignment, blade-tower interaction, and icing conditions are needed to assess long-term reliability, power gains, and fatigue benefits.
- Morphing trailing edges, adaptive Gurney flaps, and shape-memory-alloy-based actuators should be developed for high-bandwidth real-time control. It is essential to investigate aspects such as reliability, redundancy, fatigue-resistant designs, and fail-safe modes designed for challenging offshore conditions.
- Deep reinforcement learning (DRL), smart controllers, and sensors should be integrated to enable autonomous flow control actuation. Digital-twin models and machine-learning-based surrogate solvers will help optimize actuator placement, timing, and power usage.
- The investigation of synergistic devices, such as VGs and plasma actuators, LEPs and suction slots, serrations and oscillatory blowing, can unlock new performance regimes. Research should quantify the combined effects of these devices on stall delay, noise suppression, load reduction, and wake stabilization.

- Optimization under real atmospheric conditions, which includes the incorporation of turbulence spectra, wind shear, veer gust loads, and inflow intermittency. Device performance must be evaluated across the full operational envelope, especially during extreme events (gusts, storms, and rapid yaw changes) from Figure 33.

CONCLUSIONS

The rapid global expansion of wind energy and the corresponding shift toward multi-megawatt turbines have intensified the need for advanced aerodynamic flow control technologies to enhance power production, improve load stability, mitigate structural fatigue, and suppress noise. In addition, the blades of larger wind turbines experience extreme turbulence, wind shear, and yaw misalignments, which result in a low lifespan and increase the overall cost of energy (COE). This review comprehensively examined the aerodynamic characteristics, performance, limitations, lift enhancement, and technology readiness level for both active and passive flow control methods. Flow-control devices provide a practical way to increase power output and aerodynamic performance while lowering loads and vibrations.

Passive methods, such as leading-edge protuberances, serrations, riblets, and conventional vortex generators, provide durability, ease of implementation, and effective performance over a broad spectrum of Reynolds numbers, frequently resulting in notable stall-delay effects and noise suppression. The devices demonstrate elevated TRLs, indicating their readiness for commercial deployment, especially in the context of retrofits and large-scale operational turbines.

Active flow-control strategies, such as plasma actuators, microjets, oscillatory blowing, adaptive flaps, and suction-based systems, exhibit significant aerodynamic authority, allowing for real-time adjustments of lift, drag, and dynamic stall behavior in turbulent or gust-prone environments. The findings indicate significant potential for reducing fatigue loads in advanced smart rotor designs. However, obstacles such as energy consumption, durability, environmental vulnerability, power-supply complexity, actuator bandwidth, and integration constraints presently restrict their comprehensive application.

The aerodynamic efficacy of several flow-control methods for performance enhancement is illustrated in this study. The maximal lift enhancement ($\Delta C_{L, \max}$) falls between 0.2 and 0.8, as shown in Figure 33. Flaps and vortex generators are already widely used in industry to increase annual energy production (AEP) in multi-MW wind turbines, and most of these technologies have successfully advanced to field testing phases (TRL 7) and are moving toward commercialization (TRL 9). Advancing TRL through full-scale testing, improving durability, leveraging AI-based control, and pioneering hybrid concepts represent the most promising pathways for future innovation.

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