

Enhancing Wind Turbine Aerodynamics with Flow Controller: A Review

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REVIEW

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Abstract

Wind turbines are vital to global renewable energy strategies, yet their aerodynamic performance often falls short of optimal levels, limiting overall efficiency and increasing operational loads. Flow controllers, devices designed to manipulate airflow around turbine blades, have emerged as a promising means of enhancing power capture while mitigating fatigue and structural stresses. This review presents a comprehensive synthesis of current research on aerodynamic optimization using flow controllers, covering both conventional and emerging technologies such as vortex generators, Gurney flaps, microtabs, and plasma actuators. The review evaluates the aerodynamic principles behind these devices, their reported performance improvements in laboratory and field studies, and their potential to extend turbine life and improve energy yield across various wind regimes. Additionally, it examines design considerations, including scalability, integration challenges, and potential trade-offs between efficiency gains and structural integrity. Knowledge gaps, particularly in long-term field validation, controller–turbine interaction modeling, and cost-benefit analysis, are also identified, along with future research directions to address these gaps. By consolidating existing findings, this study provides actionable insights for researchers and industry stakeholders, guiding the development of more efficient, reliable, and sustainable wind energy systems through advanced aerodynamic control solutions.

Keywords: Wind turbine aerodynamics, Flow controllers, Vortex generators, Wing-tip vortices, Efficiency optimization, Turbine blade design

1. Introduction

Wind energy is becoming an increasingly viable alternative to conventional fossil fuels for power generation. The efficiency and performance of wind turbines, key components of wind energy systems, significantly influence the overall effectiveness of wind energy production. In recent years, the use of flow controllers to optimize wind turbine aerodynamics has gained attention [1]. Research in this area focuses on developing innovative flow control strategies and optimizing the placement and configuration of these controllers on wind turbines. Wind tunnel testing and computational fluid dynamics (CFD) simulations are commonly employed to study the impact of flow controllers on turbine performance [2]. Wind

energy, a growing and promising renewable resource, has the potential to reduce reliance on fossil fuels. However, the installation and maintenance of wind turbines can be expensive, and improving their efficiency remains a constant challenge. A study by the National Renewable Energy Laboratory (NREL) suggests that increasing wind turbine efficiency by just 5 % could reduce wind energy costs by up to 9 % [3,4]. In addition, improving wind turbine efficiency means fewer turbines are needed to meet the same energy demand, as each turbine can generate more power. A study by the European Wind Energy Association (EWEA) found that a mere 1 % improvement in turbine efficiency can reduce the total number of turbines required by 2.5 %, thereby lessening the environmental impact of wind energy [5–7].

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Enhancing turbine efficiency not only lowers the cost and environmental footprint of wind energy but also promotes its broader adoption. Flow controllers, devices that modify the airflow around wind turbine blades, play a critical role in boosting performance and efficiency. These controllers work by manipulating airflow to increase lift and reduce drag and turbulence, and they can be either passive or active. By studying flow controllers, we can better understand their effects on wind turbine performance and identify optimal designs and configurations for different wind speeds and turbine setups. This knowledge is essential for the continued advancement of wind energy technology. Flow controllers can be integrated into the nacelles or blades of wind turbines to manage the airflow around the rotor, further enhancing turbine efficiency [8].

Flow controllers can significantly enhance the aerodynamic performance of wind turbines, increasing their output and efficiency by modifying airflow. Various types of flow controllers, such as synthetic jets, plasma actuators, and vortex generators, are used to achieve these improvements. One major benefit of using flow controllers is the reduction of aerodynamic loads on wind turbine blades, which can extend the lifespan of the turbines and reduce maintenance costs [9]. Additionally, flow controllers help mitigate issues like turbulence and stall, which can otherwise decrease the turbine's overall efficiency. Passive flow controllers operate without an external power source, relying instead on their design to function without energy or moving parts [1]. These controllers aim to reduce aerodynamic loads on wind turbine blades, thereby extending the turbine's life and reducing maintenance needs. By minimizing turbulence and improving the blades' angle of attack, passive flow controllers can also enhance the turbine's overall efficiency. Their ease of retrofitting into existing wind turbines, along with the significant performance gains they offer at relatively low cost and maintenance requirements, has made them increasingly popular in the wind energy industry. On the other hand, active flow controllers require an external power source, typically electricity, to operate [10]. Unlike passive controllers, active flow controllers use sensors, actuators, and control systems to actively manage the airflow around the blades. Their primary methods involve reducing turbulence and optimizing the angle of attack, leading to improved turbine performance. Passive flow controllers are cost-effective, simpler in design, and require less maintenance. However, they have limitations, such as a restricted effective

range and a tendency to generate higher noise levels. In contrast, active flow controllers offer greater control over airflow and can adapt to changing wind conditions, though they require more complex maintenance routines and control systems [10]. Further research is needed to optimize these controllers for different wind speeds and turbine types. Fig. 1 illustrates the placement and arrangement of various flow controllers on a blade. Studies have shown that optimizing the design and setup of flow controllers can significantly enhance wind turbine performance. Understanding the geometry and configuration of these controllers is also crucial for developing more cost-effective and efficient wind turbines [11]. By studying how different flow controllers operate and how their configurations and geometries impact turbine performance, researchers and engineers can create more effective solutions that can be integrated into wind turbines. Additionally, exploring the geometry and design of flow controllers can deepen our understanding of the complex aerodynamic flow patterns around wind turbines, leading to the development of more accurate and reliable computational models for predicting wind turbine performance and optimizing design [12].

Wind turbine efficiency is limited by suboptimal aerodynamic performance, resulting in reduced power output and increased costs. While flow controllers have shown promise in improving aerodynamic performance, a comprehensive review of their application in wind turbines is lacking, hindering the development of optimized solutions. Previous studies, such as [14,21], have provided important insights into flow-control devices for improving wind turbine performance. However, these studies primarily focus on cataloguing existing technologies without offering a comprehensive analysis of their comparative effectiveness, scalability, and integration challenges. This review builds upon and extends prior work by incorporating the latest computational and field-based findings, offering a critical evaluation of performance improvements, structural implications, and techno-economic considerations. In doing so, it provides an updated, integrative perspective designed to inform both academic research and industrial practice. This review aims to bridge the knowledge gap by synthesizing existing research on flow controllers for wind turbine aerodynamics, identifying key challenges and opportunities, and outlining future directions for optimization and integration. The goal of this article is also to provide a thorough overview of flow controllers, which are used to increase the power generation of wind

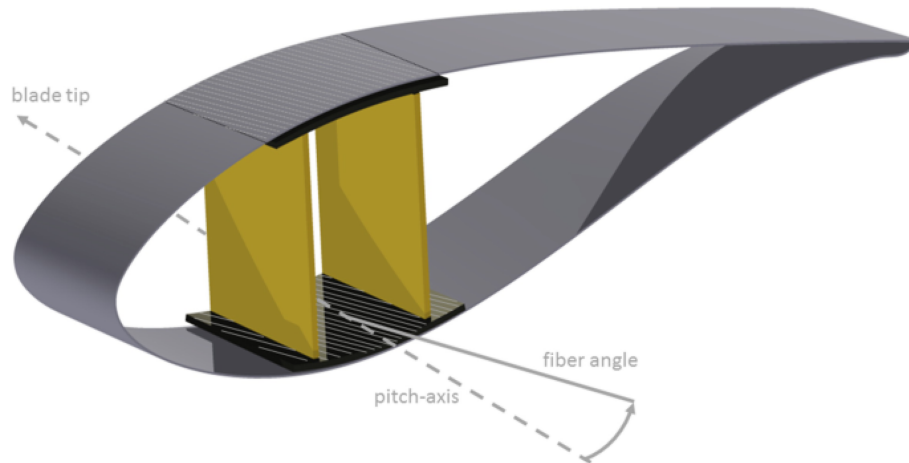


Fig. 1. Optimizing flow controller location and configuration for enhanced blade aerodynamics [10].

turbines. This includes information on how flow controllers affect performance improvement, how well they perform at each TSR regime with different geometrical parameters, and other noteworthy advantages, disadvantages, and benefits.

2. Self-sustaining flow control

Flap-type passive flow controllers offer a practical solution for modifying flow characteristics in aerodynamic systems. These controllers enhance aerodynamic performance and efficiency by altering flow patterns and turbulence levels. By adjusting the pressure distribution and flow patterns on an aircraft wing's surface, they can increase lift and reduce drag. Additionally, by influencing boundary layer separation and vortex shedding, these controllers further optimize flow patterns to decrease drag. In wind turbines, passive flow controllers are innovative devices designed to improve aerodynamic performance by altering the airflow around the blades [13]. Unlike active flow control systems, which require energy to modify the flow, passive flow controllers achieve the same goals through creative geometry and design, without needing additional power input. By leveraging the natural flow characteristics of the wind, these controllers can significantly enhance turbine efficiency and power output, increasing lift, reducing drag, and minimizing turbulence [11,12]. These devices offer a simple, cost-effective, and maintenance-free solution for enhancing wind turbine performance, with the potential to revolutionize the wind energy industry. Given the growing demand for renewable energy and the need to optimize energy production, passive flow controllers are an attractive option for wind farm operators and manufacturers looking to maximize their returns.

2.1. Cavity

Zhu et al. (2018) describe cavities as geometric modifications resembling carved grooves on an airfoil's surface. Using 2D Direct Numerical Simulations (DNS), investigated the flow behavior of a NACA0018 aerofoil with a cavity located on its leading edge at a Reynolds number of 2×10^4 and various angles of attack [14]. Their research indicated that such cavities can generate vortices that energize the shear layer, reduce separation bubbles, and delay the separation point downstream of the airfoil, as illustrated in Fig. 2. Research on cavities primarily focuses on their positioning relative to the chord length and the optimization of geometric characteristics such as diameter, opening, depth, and edge profiles (sharp or chamfered). [15] conducted a detailed study of different arc cavity configurations, examining the effects of cavity diameter, position, shape, and dual-cavity modes on the torque and pressure coefficients of a Darrieus wind turbine across various tip speed ratios (TSR). Their findings revealed that the highest pressure and torque coefficients were achieved when the cavity was positioned on the suction side and near the trailing edge. Furthermore, they noted that employing a dual-cavity mode on both the upper and lower surfaces (trailing edge) increased the power coefficient by 17 % at $TSR = 3.5$.

Vuddagiri et al. (2019) studied the effects of sharp versus chamfered edges of circular cavities positioned on the leading or trailing edges of NACA0018 and NACA0024 aerofoils. Their results showed that placing the cavity close to the trailing edge of the NACA0018 increased the stall angle from 14 to 20° at a Reynolds number of $1 \text{ E}+6$. Conversely, for the NACA0024 at a Reynolds number of 1.5×10^5 , the use of leading-edge cavities

resulted in a reduced lift-to-drag ratio despite delaying the separation point from 60 % to 68 % of the chord length. They also found that cavities with sharp edges, which confine vortices more effectively, had better lift and drag coefficients compared to those with chamfered edges [16]. In another study of [17] used a genetic algorithm to optimize sixteen different shape factors for the aerofoil, aiming to delay the stall point, which occurs at an angle of attack of 14° . Diwe et al. (2020) conducted parametric simulations on the NACA4415 airfoil, evaluating arc and rectangular cavity cross-profiles. They discovered that the recess depth ratio (h/δ , where δ is the baseline boundary thickness and h is the groove depth) is crucial for cavity shape, with the optimal ratio between 1 and 1.5. Additionally, they determined that the ideal position for the cavity's end point is around 16 % of the chord length. Overall, their findings suggest that a rectangular groove with a h/δ ratio of 1.2–1.5 performs better at effectively containing flow within the cavity compared to an arc cross-profile [18,19].

R.I. Pranto [20] examined the effects of triangular cavities on the aerodynamic performance of a NACA4312 airfoil at a Reynolds number of 5×10^4 . They tested triangular cavity profiles with depths of 2.5 % and 5 % of the chord length, positioned at 10 %, 25 %, and 50 % of the chord length on the suction side. Their results showed that a triangular cavity with a depth of 2.5 % of the chord length, placed at 10 % of the chord length, improved aerodynamic performance by 52 % at an 8-degree angle of attack. The performance also increased by 17 % and 11 % when the cavity was positioned at 25 % and 50 % of the chord length, respectively as shown in Fig. 2. Deeper cavities enhanced performance by up to 13 %, 22 %, and 14 % for angles of attack between 6 and 10° . The study also utilized the RANS transition turbulence model to provide a more accurate representation of turbulence effects. Additionally, they also investigated flow over a Risà airfoil with two types of optimized cavities at a Reynolds number of 2×10^4 and angles of attack of 3, 6, and 9° , using the high-order penalized vortex approach to solve the turbulence.

2.2. Vortex generator

According to Taylor (1947), vortex generators (VGs) are small fins attached to the base of wind turbine blades or placed over aerofoils. These passive flow control devices induce vortices in the airflow to prevent and delay flow separation. They interact with the boundary layer to introduce strong momentum flow, counteracting the reversed pressure gradient. VGs are versatile and can be used in both high and low Reynolds number scenarios, including transonic aerofoils and turbine blades. Despite their similar function, VGs come in various geometries, including vanes (such as co-rotating or counter-rotating delta, rectangular, and trapezoidal), wheelers (like wishbone and doublet), and ramps (backward/forward), as depicted in Fig. 3 [21,22]. While some studies have focused on developing innovative vortex generator (VG) designs, many have concentrated on refining the geometric parameters of traditional VGs, such as length, skew/pitch angles, and their placement relative to chord length. Computational studies by Förster and White have aimed to design and optimize VG shapes for improved aerodynamic performance across various aerofoils and Reynolds numbers [23,24]. To minimize computational costs, most of these studies have focused on a single aerofoil or a limited section of a wind turbine blade or wing. In addition to static VGs with fixed heights, research has explored two types of dynamic VGs: Smart Vortex Generators (SVGs) and High-frequency Micro Vortex Generators (HiMVGs). SVGs can extend from their casing on the aerofoil to delay flow separation, while HiMVGs operate at high frequencies to generate intermittent vortices, reducing or eliminating the parasitic drag associated with static VGs [25].

The placement of vortex generators (VGs) relative to chord length (x/c) is a crucial factor in their design. This parameter significantly influences VG effectiveness and has been a focal point in numerous numerical studies. Research indicates that positioning VGs at 15–20 % of the chord length can greatly enhance aerodynamic efficiency, especially at angles of attack between 10° and 20° .

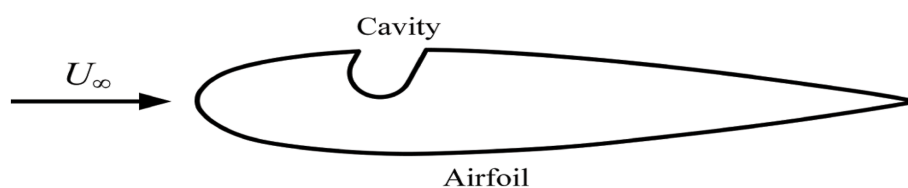


Fig. 2. The form of a cavity-filled aerofoil [20].

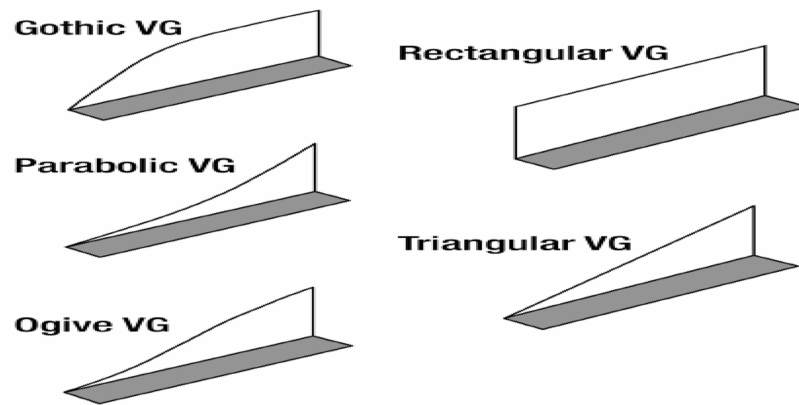


Fig. 3. Conventional VGs' shapes [21,22].

Conversely, VGs placed either too far upstream or downstream can lead to reduced aerodynamic performance. When positioned downstream, the flow may detach from the aerofoil due to increased boundary layer thickness and weakened vortices. On the other hand, VGs located too far upstream can cause vortices to dissipate before reaching the separation point, diminishing their effectiveness [26].

The height of vortex generators (VGs) is a key parameter, influenced by the boundary layer thickness, as noted by [26]. VGs are typically designed to match the boundary layer thickness where they are installed. Increasing the height of VGs can enhance lift generation, as higher VGs allow high-momentum airflow from upper levels to be introduced into the boundary layer and remain attached to the surface. However, this increase in height also comes with a trade-off: a rise in drag force. Therefore, optimizing VG height requires careful evaluation of the aerodynamic performance curve [22]. S. C. Yen et al, [27] introduced micro vortex generators (MVGs) with heights smaller than the boundary layer thickness. MVGs are particularly useful for low Reynolds numbers due to their reduced parasitic drag. While MVGs generate weaker vortices, their lower drag can make them a preferable choice, though their placement must be precisely chosen for optimal performance. The length of VGs has generally been considered fixed in most studies, with limited investigation into its effects. K. Kord [21] tested VGs of 17 mm and 20.4 mm in length and found that extending VG length did not significantly improve lift force but did lead to increased parasitic drag, thus reducing overall aerodynamic performance (Table 1). Research suggests that optimizing the spacing

Table 1. Primary VG parameters examined in Gao's study [28].

Case No.	H (mm)	L (mm)	a (mm)	b (mm)	β (°)
VGs1	5	17	10	25	16.4
VGs2	6	17	10	25	16.4
VGs3	6	17	12	30	16.4
VGs4	6	20.4	12	30	16.4

between vortex generators (VGs) is crucial for improving aerodynamic performance. O. Yirtici [28] found that increasing the spacing between VGs can enhance performance. Drezois et al. (2020) also studied the effects of VG spacing and found that if the distance between VGs is too small ($\lambda/h < 6$), the vortices can become self-destructive, leading to reduced aerodynamic efficiency [29]. Furthermore, their research on the skew angle (β) revealed that angles between 10° and 20° relative to the flow direction yield the highest lift force.

3. Flow control dynamics

3.1. Micro tab and compact jet

Microtabs are small, adjustable tabs typically placed near the trailing edge of an aerofoil on either side of the blade. First introduced by Yen and Van Dam in 2005 as a practical active load control system, microtabs alter the camber and shift the stagnation point, thereby modifying the Kutta condition [30]. They utilized a microtab device in numerical flow simulations around an aerofoil, with the results depicted in Fig. 4. When fluid flow encounters the microtab, it creates a low-pressure region behind the tab, resulting in a circular vortex that moves the flow downward along the trailing edge and generates a nose-up moment. This causes a

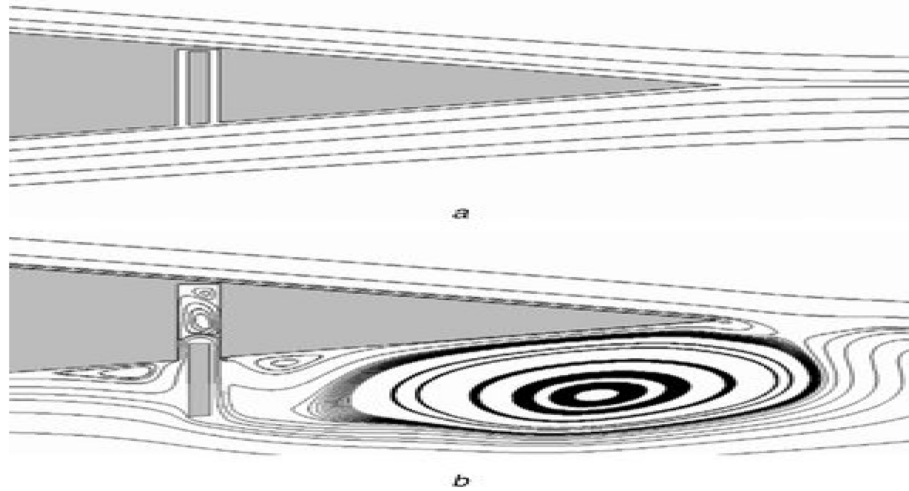


Fig. 4. Flow control at the microscale [31].

temporary decrease in lift until the vortex reaches the trailing edge. Notably, some of the flow from the upper surface merges with the vortex from the lower surface, and the combined flow exits the airfoil's surface at the new stagnation point. Despite its effectiveness and ease of use, microtabs are criticized for their delayed response compared to other active flow control systems.

Z. Wang [32] conducted a sensitivity analysis to determine the optimal microtab design for enhancing efficiency. They evaluated the S809 wind turbine blade aerofoil from the National Renewable Energy Laboratory (NREL) and the high-lift, low-drag GU25-5(11)-8 aerofoil developed at the University of Glasgow. Their study focused on the tab's height and its placement on the lower (pressure) or upper (suction) surfaces. Following this, J.P. Baker et al. (2016). Conducted further investigations using the S809 as a baseline profile [33]. Both studies revealed that placing the tab on the lower (pressure) surface enhances lift, whereas positioning it on the upper (suction) surface reduces lift and alters pressure on the suction side. Their simulations of microtabs with varying heights and positions indicated that greater tab heights and placements closer to the trailing edge yielded better performance. A tab positioned too far ahead of the trailing edge resulted in lift loss due to inadequate flow separation control and reattachment as shown in Fig. 5. Ultimately, the geometric and aerodynamic properties of the baseline airfoil are crucial in determining the optimal location and height for the tab to maximize lift.

Another study explored the relationship between lift-to-drag ratios and tab solidity, revealing a significant linear correlation between increased lift

and the tab's solidity ratio. This means that gap spacing influences pressure distribution by reducing the load on the pressure side of the aerofoil and decreasing the suction peak (Mayda et al., 2005). It was found that gaps can decrease efficiency by 6–7 % compared to a gapless tab covering the entire model. Fernandez-Gamiz et al. (2017) conducted a parametric study using CFD simulations on a micro tab installed on the pressure side of the DU91W (2)250 aerofoil, commonly used in wind turbines. Their results indicated an increase in average turbine output when micro tabs were used on 5 MW wind turbines. Similarly, three-dimensional studies by Chen and Qin (2017) and Ebrahimi and Movahhedi (2018) demonstrated the effectiveness of micro tabs in enhancing the performance of horizontal axis wind turbine blades [34]. Micro tabs have a simple design and can be integrated with other flow control devices for improved performance. For instance, recent applications have combined trailing-edge flaps with micro tabs to boost wind turbine blade efficiency, resulting in a significant 25 % increase in the maximum lift coefficient and a delay in airflow stall [35]. [36] proposed an innovative concept of integrating micro tabs with leading-edge slats. Numerical results showed that this combination could prevent flow separation and significantly enhance the aerodynamic properties of the S809 airfoil, achieving a lift coefficient 171 % higher than that of a clean aerofoil.

Recent research aimed at maximizing the lift-to-drag ratio has proposed using pneumatic jets, or microjets, to discharge flow perpendicularly from an aerofoil's surface. These small jets, positioned near the trailing edge, alter Kutta's condition by

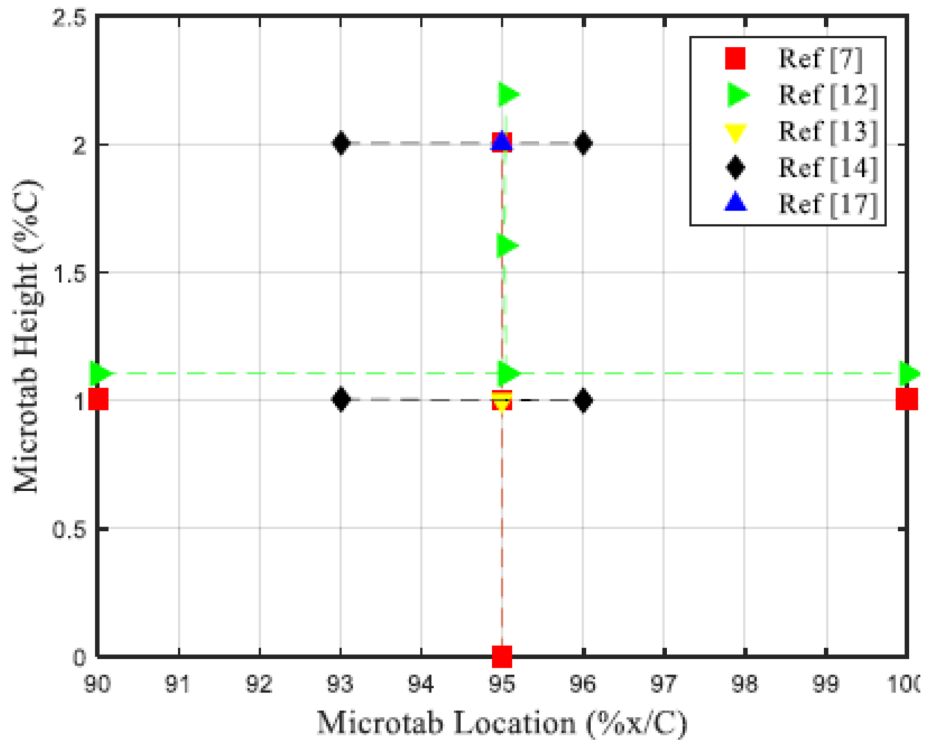


Fig. 5. Studied geometrical parameters of micro tab [33].

blowing air perpendicular to the surface. This approach contrasts with the long-standing research on tangential blowers, which have been used to adjust the boundary layer's momentum balance to keep flow attached and delay stall [37]. While tangential blowers aim to modify the boundary layer's momentum to maintain surface attachment, microjets create vortices that change Kutta's condition, impacting lift force depending on their placement on the aerofoil as shown in Fig. 6 [21]. O. Erkan [38] demonstrated the efficacy of CFD by comparing numerical simulations with wind tunnel

tests of microjets, showing promising results. O. Erkan [39] conducted further research to compare microtabs and pneumatic jets directly, finding that both have similar effects on flow along the trailing edges, leading to comparable aerodynamic characteristics. Notably, while microjets generally produce about 30 % less drag than microtabs, making them potentially more advantageous in terms of aerodynamic performance, factors such as cost, ease of installation, and operational conditions must also be considered before choosing between them.

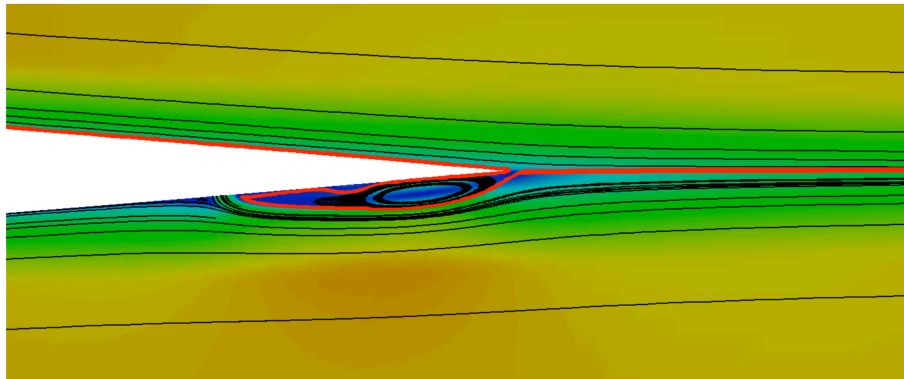


Fig. 6. The immediate streak lines surrounding an airfoil's trailing edge region that have a microjet on the pressure side [21].

3.2. Plasma actuators

Two thin copper electrodes wired at a sizable voltage differential and positioned asymmetrically, separated by a dielectric substance, make up the plasma actuator. One electrode is in contact with the ambient air, while the other is encased in a dielectric substance as shown in Fig. 7 [40–42]. The plasma actuator functions as a source of external momentum to the fluid with a zero-mass flow by physically creating a wall jet on the surface. A plasma discharge forms on the surface above the encapsulated electrode upon application of AC voltage, and directed momentum is coupled into the ambient air [43,44]. Q. Li [45] studied the NACA 0015 airfoil under stall conditions with a 15-degree angle of attack and a Reynolds number of 45,000. In their simulations, plasma actuators were placed near both the leading and trailing edges of the airfoil. They used high-accuracy compressible Navier–Stokes equations and anticipated a linear distribution of plasma force. Their findings revealed that significant plasma force could effectively eliminate stall, increasing the stall angle from 15 to 21°. The simulations showed consistent results between the 2D and 3D models once stall was removed. However, in the presence of stall, the 2D and 3D results diverged due to the lack of spanwise breakdown vortices in the 2D model. P. Mičko [46] examined the S825 wind turbine airfoil under a flow with a 22.1-degree angle of attack and a Reynolds number of 760,000. They observed significant separation near the leading edge and a drag-to-lift ratio increasing from 2.25 to 6.52. Increasing plasma momentum prevented boundary layer separation near the leading edge but was insufficient to fully eliminate the separation gap. [47] investigated the DU 91-W2-250 airfoil with various angles of attack and plasma actuators positioned at different chord lengths. Their results indicated a notable reduction or complete elimination of the separated flow area. With multiple plasma actuators, the stall angle

increased to 28°, the lift coefficient rose by 160 %, and separation was significantly delayed. The effects of different plasma types on the maximum lift coefficient and stall angle are illustrated in Fig. 8.

The number of plasma actuators used on an airfoil is a crucial factor in performance enhancement. [48] demonstrated that for a 5 MW NREL wind turbine, the power output improved with the addition of 2, 3, or 4 plasma actuators, with the turbines' speed increasing as the actuators moved closer to the turbine's center. The increase in the number of plasma actuators led to higher torque, rotor output power, and aerodynamic force production, resulting in power output increases of 0.66 %, 0.77 %, and 0.85 %, respectively. [49] conducted both numerical and experimental studies on the NACA 0018 airfoil, examining flow speeds of 30 and 65 m/s, Reynolds numbers of 330,000 and 715,000, and angles of attack ranging from 0 to 20° (in 2-degree increments). Their studies involved placing three and five plasma actuators on the pressure and suction sides of the airfoil, respectively [50]. At moderate angles of attack (counter flow), actuators on the pressure side of the airfoil enhance the lift coefficient, while those on the suction side nearly eliminate flow separation. However, at higher attack angles and speeds, the effectiveness of these actuators diminishes. Generally, for flows with a Reynolds number of 330,000, plasma actuators might be effective if newer, thicker dielectric materials are employed. [51] investigated the effects of plasma actuators positioned near the leading edge (0.04 chord length) on a DU21 wind turbine. Their study found that increasing the length and conductivity of the embedded electrode can limit the maximum performance. Additionally, increasing the thickness of the electrode and dielectric layers reduces the plasma effect. [52] explored the benefits of plasma actuators on the NACA 0012 airfoil, evaluating three near-wall turbulence models. The study concluded that the transition-sensitive Bianchini

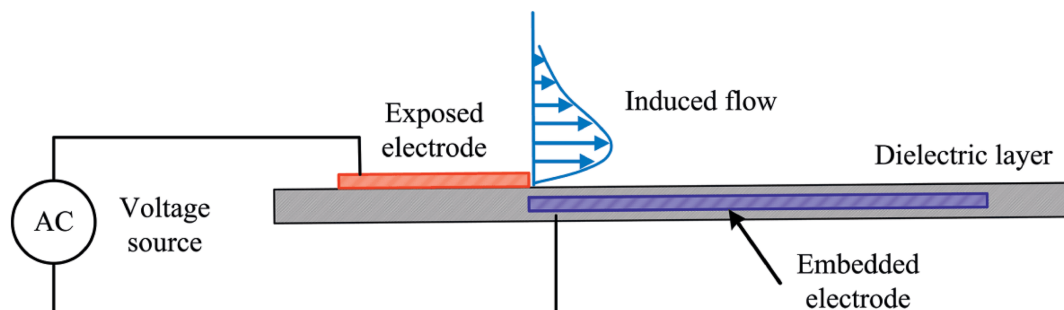


Fig. 7. The plasma actuator [40,41].

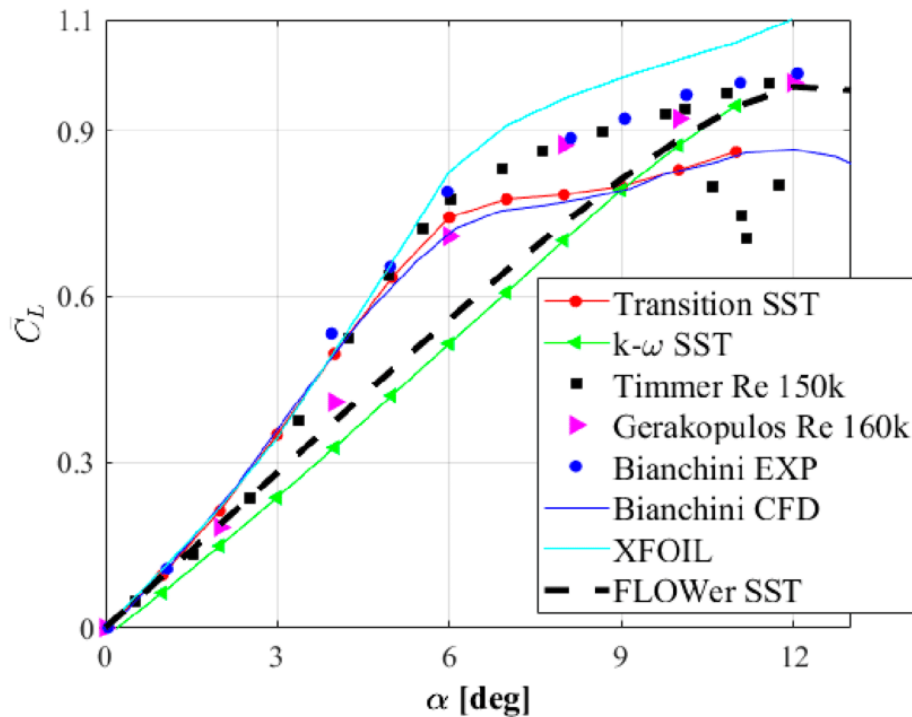


Fig. 8. Impact of single/tandem actuators on the percentage increase in the stall angle and maximum lift coefficient when compared to a clean aerofoil [46].

model was the most effective for capturing the benefits of plasma installation.

A wind turbine containing plasma on the leading edge is examined by Li Guoqiang et al. (2020) [50,53]. Investigations into the differences between pulsed and continuous plasma actuators have led to the conclusion that pulsed plasma can be more advantageous than continuous plasma in addition to conserving energy. The boundary layer transition is readily controlled by the actuator in weak stalls. The momentum blending with the flow is increased. Simultaneously, the actuator avoids the presence of huge vortices in the dynamic stall by moving the separation position backward in higher stall states. Once the plasma is activated, it may generate a negative pressure bulge site that causes unstable vortices to return to the airfoil's surface, increasing lift (At the leading edge, there are more suction peaks, and the reverse pressure gradient is recovered close to it, increasing lift). A vertical axis turbine with varying flow rates is studied in one study [54], where the plasma is mounted separately in various sections. In the end, it was determined that pulse plasma is best suited for vertical axis turbines and is at its strongest at angles between 60 and 120°. Research is being done to find the best direction for a plasma jet on various wind turbine blades. The oscillating NACA 23012 turbines are

examined by [55], with three microplasmas installed on the top surface and three on the bottom surface. The impact of co-flow or counterflow plasma jet flow directions on aerofoil lift suggests that at the airfoil's upper surface, the plasma jet flowing in the same direction as the flow reduces pressure and raises lift. Additionally, when the plasma jet is counterflow, it raises the lift at the pressure side. Additionally, the momentum coefficient at various attack angles is provided. Additionally, several on/off plasma techniques were used to lower the aerofoil loads and improve stability. The collected results demonstrated the turbine's increased fatigue resistance. In conclusion, the oscillating airfoil's stability can be increased by using micro-plasmas to lessen unstable loads on it. The operational parameters (voltage, frequency, and waveform) applied to the plasma actuator were the main design variables used by [56] to optimise the aerodynamic performance of a wind turbine aerofoil at Delft University (DU) in a full stall condition. The study discovered that while higher frequencies had no appreciable impact, raising the applied frequency to a certain limit improved the wind turbine airfoil's aerodynamic performance. Furthermore, a 130 % rise in the lift coefficient was noted, and raising the voltage led to a constant improvement in the aerodynamic performance.

Ultimately, the investigation looked at three different waveforms for the applied voltage and discovered that the rectangular waveform produced a more significant lift coefficient. Additionally, the DU 96-W-180 two-dimensional wind turbine was employed in an experimental and numerical investigation by [53,57]. The angles of attack vary from around 0 to 15°, and the flow velocities are 12.6 and 16.30 m/s. To look into the boundary layer's separation, the plasma actuator is simultaneously situated upstream and at the suction side. The outcome demonstrated that the plasma actuator lowers the lift coefficient while increasing the boundary layer's thickness and separation. Table 2 provides a consolidated comparison of key flow-control devices, highlighting their operating principles, advantages, disadvantages, and cost implications. This summary enables a quick assessment of performance trade-offs and practical considerations across different technologies, supporting informed selection for research or industrial application.

4. Further discussion

4.1. Optimizing blade geometry for maximum wind energy extraction

Research indicates that the geometry of flow controllers plays a critical role in the performance of wind turbines. Designers and engineers can significantly enhance wind turbine efficiency and power output by carefully selecting and optimizing the shape of these devices. It's important to recognize that the optimal geometry may vary depending on the specific design and operating conditions of the wind turbine. The effectiveness of passive flow controllers, which include various characteristics

such as length, thickness, width, shape, and placement, is greatly influenced by their geometry. Increasing parameters like flap length, thickness, slat height, chord length, or cavity width can lead to a substantial rise in lift, with only a minor increase in drag. However, extending these dimensions beyond a certain point can lead to diminishing returns, indicating the existence of an optimal size for these flow controllers. Enhancing parameters such as cavity depth, slot height, and the height and spacing of vortex generators can significantly reduce drag. It's important to note that the performance benefits may decrease if the cavity size becomes too large. Among different shapes, the semi-circular vortex generators demonstrated the most significant performance improvements, attributed to their larger aspect ratio, which provides better flow control. Additionally, various studies have explored how the placement and orientation of flow controllers affect wind turbine performance. These studies have shown that the strategic positioning of vortex generators and slats can lead to notable reductions in drag and increases in lift. For example, some research focused on positioning a row of vortex generators at the leading edge of a wind turbine blade, while other studies recommended using slats in that location. The application of flow-control devices in wind turbine aerodynamics has shown clear potential for improving energy capture and reducing structural loads. However, the review of existing literature reveals that these benefits are highly dependent on device type, placement strategy, and operating wind regime, highlighting important trade-offs between aerodynamic gains, mechanical complexity, and cost.

Passive flow-control devices, such as vortex generators (VGs) and Gurney flaps, are the most widely

Table 2. Comparative summary of flow-control devices for wind turbine aerodynamic optimization.

Device Type	Key Principle	Advantages	Disadvantages	Cost Implications
Vortex Generators (VGs)	Delay boundary layer separation by inducing small vortices.	Improves lift; proven in the field; relatively simple to retrofit.	May increase drag at low wind speeds; performance is sensitive to placement.	Low to moderate; installation and maintenance are relatively inexpensive.
Gurney flaps	Small tabs at the trailing edge increase lift by altering the pressure distribution.	High lift-to-drag improvement; effective at small sizes.	Structural fatigue concerns; added noise potential.	Moderate; simple fabrication but requires regular inspection.
Microtabs	Deployable tabs modify local circulation and lift on demand.	Active control possible; minimal baseline drag when retracted.	Requires actuators; increases system complexity and cost.	Moderate to high; actuator reliability adds to maintenance costs.
Plasma actuators	Use ionized air to modify the boundary layer without moving parts.	No mechanical components; fast response; adaptable control.	Requires high-voltage power supply; technology not fully mature for large turbines.	High-power electronics and safety considerations increase costs.

studied due to their relatively simple design and low implementation cost. VGs have demonstrated notable improvements in delaying boundary layer separation, thereby enhancing lift and mitigating stall, with reported efficiency gains of 5–10 % in certain studies. Gurney flaps, on the other hand, are effective at increasing lift-to-drag ratios but may contribute to noise generation and induce additional structural loads over prolonged operation. Microtabs offer an advantage in being deployable on demand, minimizing drag penalties when not required; however, their reliance on actuators increases system complexity and maintenance requirements. Plasma actuators present a promising avenue for adaptive, non-mechanical flow control but remain in early stages of commercial viability due to high-voltage requirements, power losses, and durability concerns under harsh environmental conditions. One key finding from the literature is that no single flow-control device provides a universally optimal solution across all performance metrics. Devices that maximize aerodynamic efficiency often introduce additional mechanical loads or increase noise levels, which may offset their benefits in terms of fatigue life and community acceptance. Similarly, technologies with strong adaptive potential, such as microtabs and plasma actuators, face challenges in long-term reliability and integration into existing turbine architectures. These trade-offs underline the need for multi-objective design strategies that account for aerodynamic efficiency, structural integrity, acoustic performance, and cost over the turbine's operational life cycle. While experimental and computational studies demonstrate clear aerodynamic benefits, there is a shortage of long-term field data validating performance under variable atmospheric conditions, including turbulence, icing, soiling, and yaw misalignment. Moreover, economic evaluations remain limited, with only a small subset of studies considering the balance between efficiency improvements and the added cost of installation, control systems, and maintenance. Another significant gap is the limited exploration of hybrid configuration combinations of passive and active devices, which may offer synergistic effects in balancing efficiency and adaptability.

While aerodynamic benefits of flow-control devices are well documented, their commercial adoption depends equally on cost-effectiveness, ease of manufacture, and suitability for large-scale field deployment. Passive devices such as vortex generators and Gurney flaps are relatively low-cost to fabricate using composite or lightweight polymeric materials and can be retrofitted to existing

blades with minimal modifications. Their manufacturability is straightforward, though precision in placement and alignment remains critical for performance consistency. Active devices like microtabs and plasma actuators, while offering adaptive control, involve higher capital costs due to actuators, sensors, and associated control hardware. Plasma actuators, in particular, face additional challenges related to power electronics, thermal management, and environmental durability, making them less mature for immediate industry application.

Field applicability further depends on device robustness under conditions such as icing, erosion, and prolonged exposure to UV and moisture. Long-term maintenance requirements also influence cost-benefit analyses. Hence, future research should integrate techno-economic modeling with aerodynamic performance studies to guide practical deployment in commercial wind turbines.

4.2. Optimizing flow controller performance across TSR ranges

The tip speed ratio (TSR), which is the ratio of the blade tip's tangential speed to the wind speed, is a critical factor in wind energy systems that affects the control, safety, efficiency, and design of wind turbines. A deeper understanding of TSR can improve wind turbine performance and reliability, accelerating the adoption of wind energy as a sustainable resource. Passive flow controllers can vary in effectiveness depending on the TSR of the wind turbine. At low TSRs, these controllers can improve aerodynamic performance by reducing turbulence and delaying stall onset. When a blade's angle of attack is too steep, airflow can separate from the blade's surface, leading to reduced lift and stall. Passive flow controllers help by postponing stall and enhancing lift, thereby increasing the turbine's power output. At high TSRs, passive flow controllers also contribute to improved aerodynamic performance by adjusting the airflow around the blade and reducing turbulence. However, their effectiveness is influenced by factors such as the design of the controller, the Reynolds number of the flow, and other variables. [Table 3](#) provides a summary of how different passive flow controllers perform across various TSR ranges.

5. Conclusions

The reviewed literature demonstrates that flow-control devices can enhance wind turbine performance by 5–15 % in power output and reduce aerodynamic loads by 10–20 %, depending on

Table 3. Performance of passive flow controllers at different TSRs [21].

Flow controller type	Performances	The typical regime of TSR	Other factors that affect optimal TSR	References
Gurney flap	Higher TSR	Between 7 and 9	Blade pitch angle and the wind speed.	[58,66]
Fixed trailing edge flap	Lower TSR	3–6	Blade twist angle and the wind speed.	[59,67]
Microcylinder	Intermediate TSR	5–8	Values the spacing between the microcylinders and the blade surface	[45,60]
Cavity	Lower TSR	4–7	The cavity size and spacing	[38,61]
Vortex generator	Intermediate TSR	3–6	The generator size and spacing	[39,62]
j- type blade	Intermediate TSR	3–8	The twist angle	[36,63]
Leading-edge slat	Intermediate TSR	5–8	The specific design of the wind turbine and the size of the slat.	[64,65]
Slot	Below TSR	5–9	The size of the slot	[40,65]

device type, geometry, and placement. Vortex generators, for instance, have consistently shown efficiency improvements of 5–10 % by delaying boundary layer separation, while Gurney flaps and microtabs can further increase lift-to-drag ratios, albeit with trade-offs in noise and structural fatigue. Plasma actuators, though still in early stages of field application, indicate potential for high-frequency adaptive control with efficiency gains of up to 12 % in controlled type.

Despite these promising results, large-scale field validations remain limited, particularly under turbulent, icing, or soiling conditions. Moreover, comprehensive techno-economic analyses are scarce, leaving uncertainties about lifecycle costs and industrial scalability. The findings suggest that future research should focus on multi-objective optimization that balances aerodynamic performance, structural integrity, acoustic emissions, and cost-effectiveness. Hybrid approaches combining passive and active flow controllers, along with smart control algorithms, offer promising pathways toward next-generation wind turbines. This review provides an integrated knowledge base to support the development of more efficient, durable, and economically viable aerodynamic enhancement strategies for wind energy systems.

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Conflicts of Interest

The authors declare that they have no conflicts of interest concerning the publication of this paper.

Ethical Approval

The author(s) affirm that this study adheres to ethical standards and principles.

Data Availability

No data availability.

Author Contributions

Oluwaseyi O. ALABI: Conceptualization, Methodology, Software. **Adewale R. INAOLAJI:** Writing-Original draft preparation. **Oluwaseyi Omotayo ALABI:** Writing- Reviewing and Editing. **Monsuru O. MUFUTAU:** Visualization, Investigation. **Oluwaseyi O. ALABI:** Supervision and Validation.

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