Horizontal axis wind turbines passive flow control methods: a review

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Abstract. In improving wind turbine torque and power output, the aerodynamic characteristics of wind turbines blades play an important role. Unleashing easy but efficient flow enhancement techniques over aerofoil sections used in horizontal axis wind turbines (HAWT) has become essential in the increasing demand for this source of renewable energy. These techniques or methods are primarily categorized into two kinds: active and passive. Active methods of flow control need energy expense whereas passive flow control methods are needless of auxiliary power. This paper investigates various passive flow control strategies that have great potential to boost the aerodynamics of blades of HAWT. The mechanisms and working principles, along with the findings from various experimental studies and CFD results for passive flow control systems are included in this article. Also, some of these studies are supported by demonstrating the lift and coefficient of drag (CD) variation with the angle of attack (AoA). The review suggests simple, cost-effective ways of improving lift and controlling the aerofoil stalling behaviors to obtain higher power efficiency for HAWT.

Keywords: Horizontal Axis Wind Turbine, Passive Flow Control Methods, Stalling Angle, HAWT

1. Introduction

Energy has been an essential force of unmatched levels of growth, prosperity, and economic change over the past century, leading to a drastic increase in its needs. Several primary energy sources have enjoyed popularity during this period, including coal, oil, and natural gas, solely because of the industrial and transport sectors [1]. These fossil fuels are, however, polluting and their reserves are limited. Therefore, as our demand is ever-growing with limited natural resources, global energy crises are bound to occur. Besides, there has been a substantial increase in the number of greenhouse gases [2]. This has led individuals all around the world to use clean and green energy sources to counter growing environmental deterioration and depletion of natural resource reserves. Some of the renewable energy sources include wind, solar, geothermal, etc. With rapid advancement and accessibility of all different sized aeromotors, wind power is considered to be the key source of energy among other energy sources [3]. There are many studies on different methods proposed to optimize the generation of wind turbine power. The effectiveness and efficiency of a wind turbine [4] get influenced by many parameters. The wind turbine blade, which consists of aerofoil surfaces, is one of many parameters that affect power output (efficiency) of a wind turbine. The aerofoil aerodynamic characteristics have a direct effect on the
performance and therefore the design of aerofoils is of prime importance [5]. The optimization of the aerofoil configuration thus plays a prominent role in nurturing the aerodynamic power and robustness of the blade of the wind turbine [6]. To boost a wind turbine's aerodynamic efficiency, numerous techniques have been researched. Two key variables need to be considered for determining the efficiency of an aerofoil, namely, the coefficient of lift and the lift-to-drag ratio. Apart from these two key variables, flow separation is also one of the major issues in the field of aerofoil fluid mechanics. There are two methods often used to delay the flow separation over an aerofoil which are the active and the passive method[7], to enhance the overall efficiency of an aerofoil.

The methods for active flow control require energy expenditure and may consist of one or more moving parts mounted on the body of the aerofoil. Ailerons, deformable or inflatable membranes called stall ribs, controllable and movable spoilers, jet actuators, plasma actuators, etc. are some examples of active flow control methods [8]. Alternatively, the methods for passive control require no external power. It consists of stationary parts attached to the turbine aerofoils for their operation. Vortilons, flow vanes, gurney flaps, fixed leading edge slats, aerofoils with protuberances, cavities, and passages are some of the examples of passive flow control approaches [9]. This paper investigates the structure, efficiency, and operation of various passive flow control methods for an aerofoil that are developed in the past two decades, then effectively improves the overall power output of a wind turbine.

2 Aerofoil flow control methods.

Over the last century, the boundary layer transition from laminar to transient, the phenomena of flow separation had become the topic of extensive investigation for many researchers. Consequently, their boundary layer separation controls still involve many open and critical issues with practical challenges in their solutions. Researchers have developed different methods that can be used on an aerofoil to help delay the detachment of flow over boundary layer [10]. The active and passive flow control methods are two types of methods used for this purpose.

2.1 Active Flow Control Methods.

Flow field management in selected parts of the wind turbine blade issued by active control methods to bring out the desirable effect. The active flow control method requires auxiliary power (an energy source); thus, the performance advantage of this technique must cover the auxiliary energy that was used to enhance the dynamics of fluid of the aerodynamic body (energy input for an actuator). The methods of active flow control often consist of one or many moving parts attached to the original structure of the aerofoil. Depending on the different parameters, these moving parts are thus operated or deployed according to the need. Over the last decade, a significant improvement has been made in the implementation of active flow control methods for the aerofoil used in wind turbine blades. The primary focus has been on managing the vibration (due to unstable aerodynamic blade loads). This is done by controlling the flow over the blade locally. Some examples of active flow control are stall ribs, ailerons, spoilers, and various types of actuators. The two most popular types of actuators are the plasma actuator and the piezoelectric synthetic jet actuator. The plasma actuator ionizes the flowing air around the two electrodes. Thus, air is accelerated by an electric field over the blades. These methods (active) are typically more costly and need more maintenance when compared with the passive flow control ones [11, 12].
2.2 Passive Flow Control Methods. Many researchers have used several techniques numerical or experimental techniques to investigate the effectiveness and power efficiency of passive control methods. By altering characteristics of flow in the boundary layer, passive methods control the flow over an aerofoil. This is because of the mixing can be effectively controlled by modulation of flow in the separated shear layer over the blade (aerofoil). Passive flow control methods require no external energy (or extra power). In contrast, the passive flow control methods consist of stationary parts placed on the aerofoil frame and thus require less maintenance. Several researchers have favoured the use of passive flow control methods in the field of aerodynamics, as they provide cost-effective and technologically efficient solutions [13]. In this analysis, a thorough study of many such passive flow control methods is reviewed.

3. Passive Control (Flow) Methods

3.1 Vortex Generators and Vortilons

3.1.1 Concept of Vortex generators. The passive flow control devices were introduced and developed [14, 15] are called ad vortex generators and vortilons. Vortex generators and vortilons are methods working under the same general principle. These attachments aim to produce vortices that boost the mixing of the free flow that spreads downstream. As a result, there is re-energization of the boundary layer and hence the flow is stuck to the surface of the aerofoil for a longer time. These devices have many shapes and consist of thin vertical plates that are typically placed in their simplest form on the wing. To restrict the flow separation [16], Vortex Generators and Vortilons can also be used.

3.1.2 Structural considerations. The arrangement of Vortilons is very simple as they are passive control devices and consist of flat plates permanently fixed on the underside of the aerofoil, which is also known as the pressure side. Tiny vanes mounted on the surface (mostly upper) of the aerofoil consist of vortex generators. The material of aerofoil, design, and manufacturing process of Vortex generators and Vortilons depends on the scope and application of several parameters [17]. Fig. 1 shows the configuration of the Vortex Generator and Vortilon.

Figure 1: The location and configuration of vortilons and Vortex Generators on an aerofoil [18]

3.1.3 Aerodynamics of Vortilons and Vortex Generators. The Vortilons and Vortex Generators aim to produce strong vortices that will maintain the airflow on the aerofoil's suction side and thus delay the stall. Their key benefit is that the small penalty on parasitic drag combines with strong stabilizing effects of flow. Vortilons are positioned so that they extend in front of the leading edge on aerofoil pressure side so
that it intersects with stagnation streamline at a greater angle of attack (AoA) to obtain vortex creation at very greater angles of attack (AoA). In combination with the location of the vortilon, the outward flow portion initiates a creation of a strong vortex on the inboard side. Thus, vortilon re-energizes the aerofoil boundary layer by free stream-boundary layer mixing. By causing a delay in the separation of the boundary layer [19]

3.1.4 CFD Results

![Figure 2. CFD analysis of NACA 23024 aerofoil [20].](image)

A CFD analysis of the NACA 23024 aerofoil was carried out in which coefficient of lift and drag were calculated and compared with and without the Vortex Generator (aerofoil) at 14.25 m/s inlet airflow velocity. Fig. 2 reflects the NACA 23024 aerofoil CFD research at a six-degree angle describing the velocity contour. Fig. 3 reflects the graphs of the attack angle against the coefficients of drag and lift taken from the CFD analysis. The study concluded that the Vortex Generator aerofoil showed an improved drag ($C_D$) and lift coefficient ($C_L$) and the delayed flow separation over the aerofoil was shown. Similar results can be anticipated for the Vortilon-mounted aerofoil [20].

![Figure 3. Variation of the $C_D$ and $C_L$ versus angle of attack (AoA) [20].](image)

3.2 Gurney Flaps

3.2.1 Concept of gurney flaps. A well-known race car driver and team manager, Dan Gurney, invented the Gurney Flaps concept in 1971. Lieback eventually applied this device in the field of aerodynamics in
1976. A basic vane, typically located on the upper and lower sides of the aerofoil at the trailing edge, is the Gurney Flap (GF). According to Liebeck, the overall lift of the aerofoil is increased by Gurney Flaps and the drag is minimized after it is correctly sized [21]. As shown in Fig. 1, a Gurney flap is a plate (flat) attached to the edge of the aerofoil at its tail. It is mounted on the surface (upper or lower) perpendicular to an aerofoil surface. It is easy to produce and evaluate a Gurney flap as it has a very basic design. A Gurney flap usually consists of a height of between 1% and 2% of the length of the aerofoil chord c to achieve an increase of approximately 30% in aerofoil \( C_L \) max [22].

![Figure 4. Gurney Flap on an aerofoil trailing edge](image1)

![Figure 5. Flow Physics around a Gurney Flap](image2)

3.2.2 **Aerodynamics of Gurney Flaps.** The flow behind a Gurney flap causes an improved camber on the aerofoil are widely accepted. Downstream of the Gurney flap (Fig. 5), vortices are formed and the difference in pressure between lower and upper trailing edge surfaces get increased. This slightly reduces recovery pressure on the upper surface. An advantage in the lift-to-drag ratio is obtained after the proper sizing of the flap. Chordwise vortices are produced in front of the flap. These become important at high angles of attack in addition to the spanwise vortices which are produced behind the flap. Therefore, there is an increased pressure ahead of the flap on the lower surface and the upper surface suction can be decreased while producing the same lift [24].

3.2.3 **CFD Results.** A CFD analysis in ANSYS Fluent software was conducted on an aerofoil of NACA 0012 with a Gurney Flap. Inlet airflow velocity was kept as 30 m / s and the CFD analysis was conducted for different angles of the attack starting from the zero-degree angle of attack. Fig. 6 (a) represents the model geometry of NACA 0012 aerofoil with Gurney Flap in ANSYS Fluent software whereas Fig. 6 (b) represents geometry of the model with mesh layer. Fig. 6 (c) represents the vortices in a 3% Gurney Flap chord. The study concluded that, the Gurney flap (GF) is a system to increase the L/D ratio. It can raise the lift coefficient by up to 30 percent, but the maximum lift to drag ratio must be considered as a drag penalty. Fig 7 (a) and (b) represent the graphs of the AoA against the coefficients of drag and lift drawn from CFD analysis [23].

![Figure 6. CFD Results](image3)
Figure 6. NACA 0012 aerofoil (CFD analysis) with Gurney Flap (a) Model Geometry (b) Mesh (c) Vortices

Figure 7. Graphs of (a) AoA vs Drag Coefficient and (b) AoA vs Lift Coefficient [23].

3.3 Leading Edge Slat

3.3.1 Concept. Leading-edge slats or slots are passive flow control devices used to enhance lift and regulate stall characteristics of an aerofoil operating at a higher angle of attack (AoA).

Figure 8. Lead edge slat

3.3.2 Structure. Slats are fixed auxiliary aerofoils mounted on the main aerofoil to form a channel that allows for a mass flow from the pressure side to the suction side of an aerofoil. Slots are similar to slats formed by separating the main aerofoil itself at different locations into single or multiple slots. Leading-edge slats were first introduced by Lachmann [26] and Handley Page [27] as flow control (passive)
methods which is extensively used to enhance lift performance at a higher angle of attacks. Weickk and Shortal [28] studied the effects of the slats and multi slots at various positions along the chord length. It has been seen that when located along the LE of the main aerofoil, symmetric auxiliary aerofoils provide better performance over cambered auxiliary aerofoils used near the aft or trailing edge [25]. As a passive flow control technique, this paper studies the effect of leading-edge lattice on HAWT aerofoils.

3.3.3 Aerodynamics of Leading-Edge Slat. Different effects as the slat effect, circulation effect, and dumping effect depend on the operating theory behind slats. The pressure gradient is lowed on the suction side of the main aerofoil in simple terms. This decreases the detachment of the boundary layer on the main aerofoil due to the high-velocity outflow of slats[29]. Even at a higher AoA, this improves the lift to drag ratio and thus regulates stalling conditions.

![Figure 10. DU97W300 and NACA 22 [30].](image)

![Figure 11. Vorticity of flow over the wing by slat](image)

3.3.4 Experimental Study

Due to the manufacturing limitations of HAWT aerofoils (it can only tolerate twisting from 8 degrees to 18 degrees), the root section stalls at high AoA. The leading-edge slats analysis was carried out using DU97W300 aerofoil (main wing) and NACA 22 as auxiliary leading-edge wing (slats) [30] to conduct tests in a wind tunnel and CFD simulations. Tests resulted in a rise in the lift at higher AoA, thereby increasing the AoA stall. At lower AoA, the drag component was found to be higher than the primary main wing characteristics, but as AoA increases the leading-edge slats delays the separation of boundary layers, leading to a reduction in pressure drag.

3.3.5 CFD Results. The authors used an OpenFoam simulator with SST turbulence (k-ω)model. Some deviations from detachment of the boundary layer in the RANS from the realistic tests conducted were obtained due to the lower sensitivity for boundary layer separation in the RANS model. However, a delay in the stall due to the use of salt [30] was observed by the simulated vorticity flow. Turbine blade simulations showed that lifting increased at higher angles on the inside of the blade and can increase the overall energy generation by 0.5-1 percent using the salt. Thus, even with an existing turbine blade with some retrofitting, it is easy to combine this with the simplicity of the slats. The simplistic construction makes its manufacturability simpler and makes it a cost-effective lift enhancing, passive flow control technique controlling stall.
3.4 Cavities

3.4.1 Concept. One of the cost-effective passive flow control strategies that can be used efficiently to maintain flow over the aerofoils is cavities. This paper explores the aerodynamic concepts behind cavities and also summarises the experimental studies on the application of cavities on HAWT aerofoils carried out by simulation.

3.4.2 Structure. Cavities of various types, such as the oval, elliptical, inclined, are rendered on the suction side (upper surface) of an aerofoil at different positions along the chord lengths. The cavity ratio (ratio of arc length to cavity curvature radius) is used at its leading edge (LE), middle centre (MC), trailing edge (TE) of an aerofoil to form varying formed cavities.

![Figure 12. Cl w.r.t. different AoA [30].](image)

![Figure 13. Wind tunnel at TU Berlin facility [30].](image)

![Figure 14. Dimensions of the cavity on an aerofoil [31].](image)

![Figure 15.(a)](image) ![Figure 15(b)](image) ![Figure 15(c)](image) ![Fig. 15(d)](image) ![Fig. 15(e)](image) ![Fig. 15(f)](image) ![Fig. 15(g)](image)

**Figure 15.** (a) LE, (b) MC, (c) TE circular shaped, (d) elliptical shaped, inclined cavity towards, (e) DSE and (f) USE respectively, (g) vertical cavity [31].
3.4.3 Aerodynamics of Cavity. The wind turbine blades in which the aerofoils work in the 5x10^5 Reynolds number face problems of boundary layer separation, bubble formation, flow transfer, and reattachment [32]. This bubble stretches over 10 to 30 percent of the length of the chord. This affects the flow over the upper surface of the aerofoil. It was found if the pressure on the suction side (upper surface) of an aerofoil does not enhance in the flow direction. The flow never detaches the boundary layer [33]. Raghunathan and Ombaka [33], Olsman and Colonius [34]. According to Hu et al.[13] and Kim et al. [35], the separation of flow over an aerofoil results in increased drag. At a higher AoA, flow separation also causes stalling. The vortices created are trapped within the cavity using the cavities and re-energize the flow over the cavity downstream. The flow over the trailing edge of the aerofoil is thus maintained, delaying the separation of the boundary layer [36]. It notes that the underlying theory behind the use of cavities is that turbulence increases, providing ample energy to flow to resist the gradient of negative pressure. This helps to increase L/D ratio, decrease noise, and improve the wind turbine blade's overall performance.

3.4.4 CFD Results. Using the RANS model on the NACA 0018 aerofoil with cavities of different shapes positioned at different places, Vuddagar and Samad [31] performed unstable flow simulation. In different positions such as the leading edge, trailing edge, middle centre, different cavity shapes such as circular, elliptical, inclined to LE, TE were mounted. Using Ansys, fluent CFD simulations were analysed to obtain lift coefficient, drag for Reynolds numbers 5x10^5 and 6x10^6 and 5 degrees and 15 degrees of AoA. A greater flow separation was observed on cavity less aerofoils. While the flow attaches at the beginning of the cavity, it cannot proceed along with the far downstream of the cavity. As compared to the LE of the aerofoil, the TE, MC cavities were able to maintain the flow. However, the overall efficiency had declined compared to cavity-free aerofoil. The results obtained by simulating flow over NACA 0012 by Patial and Yadav[32] showed a net increase of 9.44 percent in the overall aerodynamic efficiency of the aerofoil with a cavity over without a cavity. They suggested that with a cavity ratio of 0.5 to 1.25, the best location of the cavity is from 5 percent to 20 percent of LE.

The conclusion is that high-depth cavities will increase the lift-to-drag ratio, overall aerodynamic effectiveness of aerofoil when used on the TE by stall control, by using the vortex shedding method to postpone the separation of the boundary layer for low Reynolds number aerofoils as used for HAWT.

| Cavity shape          | Cl  | Cd  | ClCd |
|-----------------------|-----|-----|------|
| Without cavity        | 1.079 | 0.114 | 9.461 |
| Cavity inclined towards USE | 0.891 | 0.132 | 6.750 |
| Cavity inclined towards DSE | 0.887 | 0.133 | 6.669 |
| Elliptical cavity     | 0.930 | 0.127 | 7.332 |
| Vertical cavity       | 0.908 | 0.150 | 6.984 |
| Cavity at LE          | 0.950 | 0.128 | 7.421 |
| Cavity at MC          | 1.013 | 0.121 | 8.363 |
| Cavity at TE          | 1.043 | 0.115 | 9.069 |

*Figure 16. Cl and Cd VS AoA [31].*

*Figure 17. Results obtained at 6x10^5 RE and 15 degrees AoA [31].*
3.5 Flow Vane

3.5.1 Concept. Georgios Pechlivanoglou aus Athen established the flow vane definition in 2012 [30]. It is an idea that has not yet gained prominence, but as it proposes a method to increase the stall characteristics of wind turbine aerofoils, it seems promising. This notion is roughly based on biplane configuration and biplane theory [37].

3.5.2 Structure. The design consists of an additional profile formed by an aerofoil placed over the main profile. The additional profile is a smaller chord than the main profile, although the chord length of the auxiliary aerofoil is less than 20% of the main profile. The distance between the main aerofoil and the auxiliary aerofoil is the same as the chord length approximately [29]. Construction variables that influence the parameters of performance [37, 38] are the gap, chord, stagger, decalage, and overhand.

![Figure 18. Configuration of Flow Vane [29].](image)

3.5.3 Aerodynamics of Flow Vane. To produce a replacement for a fixed L.E Slat solution, the flow vane principle was invented [29, 30]. The flow vane aims to increase a given aerofoil's range of effective angle of attack. A sheer layer of air is created by the secondary aerofoil that prevents the separation of boundary layer on main aerofoil. The target is not to generate lift, but to postpone the separation of the airflow concerning the AoA [29].

3.5.4 Experimental Study. To demonstrate the feasibility of this idea, Georgios Pechlivanoglou from Athen [29] performed two wind tunnel experiments. These tests were conducted along with these on DU96W180 and DU97W300 aerofoils, the auxiliary aerofoil used was a NACA 22 aerofoil with chord length is 15 percent of the major profile's chord length. At two sites, the flow vane was installed and the wind tunnel experiment was performed.

![Figure 19. Flow Vane Experimental Setup [29].](image)

| Aerofoil  | Chord (m) | Thickness (% Chord) |
|-----------|-----------|---------------------|
| DU96W180  | 0.6       | 18                  |
| DU97W300  | 0.6       | 18                  |
The tests suggested that the lift changed dramatically to higher $C_L$ value for a moderate AoA. The value of $C_L$ also increased by about 50 percent. The stall was delayed by about 10 degrees. Extra drag due to the flow vane [29] decreased the coefficient of power of the aerofoil.

### 3.6. Leading Edge Protuberances

**3.6.1 Concept.** The notion of L.E. When marine biologists observed the pectoral flippers of humpback whales and found that they had structures on their leading-edge [39], protuberances were initially discovered in nature. In essence, these tubers or protuberances were leading-edge control devices that enhanced hydrodynamic performance [40].

**3.6.2 Structure.** The structure consists of tubercles placed on the leading edge of the aerofoil like structures. These are fairly complex structures and are generated on the leading edge by creating a sinusoidal profile [41].

![Figure 20](image1) Sinusoidal Waveform L.E protuberances [29].

![Figure 21](image2) Leading Edge protuberances [41].

**3.6.3 Aerodynamics of Leading-Edge Protuberances.** The idea behind L.E Protuberances is to change the surface profile of the aerofoil. But it changes the flow characteristics on the surface by introducing a sinusoidal waveform at the leading edge and induces transitions and turbulence, which can be successful in delaying stall at high AoA. In wind turbines, it is observed that the addition of L. E. Protuberances can lead to an improvement in the use of power [42, 43].

**3.6.4 Experimental Study.** Yinan Zhang, Mingming Zhang, and Chang Cai performed a wind tunnel experiment in 2019, and DU95W180, which is widely used as an aerofoil for a wind turbine, was the aerofoil chosen. The protuberances were based on humpback whale tubercles and the produced sinusoidal wave profile and amplitude of $A=0.06 \, c$ and lambda wavelength $=0.11 \, c$ [43]. All the experiments were performed in a closed-circuit wind tunnel with a maximum flow velocity of 40 m/s and a square cross-section of 500 x 500 mm and a length of 2 meters. The wind tunnel measurements showed that the wavy aerofoil showed better aerodynamic characteristics with a higher $C_l$ value and a lower $C_d$ value in the post stall area. Compared to the simple aerofoil, the aerofoil with the L.E Protuberances displays a reduced stall [43]. A similar experiment was also performed with flippers developed from a humpback whale's flippers,
and when measured against plain flippers, it was found that the tuberculous flippers had an improved stall angle. It showed a higher coefficient of lift with lower drag at higher AoA [42].

3.7 Winglet
3.7.1 Concept. By the power generation for a given blade length, Winglets improve the efficiency of wind turbine rotors, making them attractive on sites with design limitations on the rotor radius [44].

3.7.2 Structure. The construction consists of either an externally mounted curved aerofoil like structure or a 15-degree curved upward direction extension of the current blade [44]. This means that the vortex formations are reduced at the tip of the blades, which then decreases the drag caused. The length of the expanded structure is smaller in contrast. The optimum length was 15 cm [44].

3.7.3 Aerodynamics of Winglet. As winglets, extensions of the main wings are known. There are, as we know, two regions around a wind turbine, the area of high pressure and the area of low pressure. The wind passes from the region of high-pressure to the region of low-pressure at the tip of wind turbines, creating tornadoes or vortices. This phenomenon induces extensive drag, and the ratio of lift to drag decreases. Winglets are used at the tip [46] to prevent this from occurring. These winglets ensure that certain tornado formations do not occur and decrease the induced drag. The reduction in drag (total) is achieved if the drag from winglet is less blade's induced drag. The art is to build a winglet that maximizes the power output for the entire rotor [45].
3.7.4 Experimental Study. The FWLL algorithm was used by Mac Gauana & Jeppe Johansen B in 2007 and parameters for a Risø-B1-15 aerofoil were considered [47] (AoA 8 °, C_l / C_d=110 and C_l=1.4) respectively. In addition, a TSR=8 tip-speed ratio is used throughout. Computational findings obtained increased the power by the use of passage in winglet is much greater than for the corresponding length of the upwind winglet.

3.8 Passage flow
3.8.1 Concept. Havaldar et al. [48] created and published the notion of passage flow. It is another term that has not yet gained prominence but appears to be promising as it proposes to increase turbine aerofoil efficiency.

3.8.2 Structure. This aerofoil air passage is constructed in such a way that it has an inlet at leading edge (LE) of aerofoil. An outlet at the aerofoil trailing edge (TE). The architecture consists of an internal passage on the same axis that cuts through the entire aerofoil. For the wind flow through it, this is done, which gives us more productive results in return.

3.8.3 Aerodynamics of Passage Flow. At LE, the front end of the passage behaves as a suction. Airflow from the passage is combined with airflow through aerofoil. Compared to aerofoil without Internal Passage [48], this ensures separation moves towards trailing edges. By combining the flow over the aerofoil with the additional flow coming from a slot or passage, flow over the aerofoil is re-energized [49].

3.8.4 Experimental Study. To demonstrate the efficacy of this idea, Havaldar et al. performed wind tunnel experiments in 2015. These experiments were performed on NACA 2412 aerofoils which, as we can see in Fig. 25, were provided with a passage flow.

Figure 25. 3-D NACA 2412 Aerofoil with Internal Passage [48].

Figure 26. Wind tunnel testing [48]
Table 2. of Results obtained from the wind tunnel testing [48].

| Velocity(m/s) | AoA(°) | Lift (kg) Simple | Lift (kg) Slotted |
|---------------|--------|------------------|------------------|
| 0             | 0      | 0.095            | 0.095            |
| 0             | 10     | 0.095            | 0.095            |
| 20            | 30     | 0.015            | 0.035            |
| 30            | 40     | 0.025            | 0.035            |
| 60            | 0      | 0.095            | 0                |
| 10            | 10     | 0.025            | 0.035            |
| 11            | 20     | 0.03             | 0.05             |
| 30            | 40     | 0.07             | 0.075            |
| 40            | 0      | 0.025            | 0.02             |
| 10            | 10     | 0.095            | 0.095            |
| 15            | 20     | 0.095            | 0.095            |
| 30            | 40     | 0.155            | 0.145            |
| 40            | 0      | 0.035            | 0.025            |
| 10            | 10     | 0.095            | 0.07             |
| 10            | 20     | 0.125            | 0.13             |
| 30            | 30     | 0.175            | 0.19             |
| 40            | 40     | 0.215            | 0.215            |

Figure 27. Lift obtained compared with plain aerofoil [48].

4. Conclusion. The conventional aerofoils used for HAWT have some disadvantages, such as poor stalling efficiency at low speeds and higher AoA, and lower lift-to-drag ratios. The passive flow control techniques described above have been implemented to resolve this issue and have proven to be effective in increasing the overall aerodynamic efficiency of the HAWT blades. The passive flow control methods are simplistic in nature, unlike active flow control methods, since they do not require any additional means of energy to function. These strategies have been found to be highly cost-effective and can easily be applied with minimal maintenance. A review analysis of several such methods has been conducted which concludes that these methods have helped optimise $C_L$ and $C_D$, an increase in AoA, improve the characteristics of the stall, delayed the separation of flow. This increased the overall generation of energy. We may therefore conclude with the above analysis that there is great scope for research in the area of passive flow control techniques to be incorporated in the wind turbine blades to increase their overall aerodynamic efficiency which can help in yielding an increased power output.

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