

A REVIEW ON THE AERODYNAMIC FLOW CONTROL TECHNIQUES: PROGRESS AND CHALLENGES

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ABSTRACT

Aerodynamic flow control is an essential requirement for the airplane designers to achieve the minimum drag coefficient at different flight missions. A comprehensive review is focused in this article to provide the detailed insights about the works carried out by Aerodynamists on flow control. This flow control is the key parameter associated with flow separation, flow reattachment, boundary layer separation, lift enhancement, and drag reduction in the field of aerodynamics as well as hydrodynamics. The specific areas or components where the flow control is essential are known as the wings and tails of airplanes, compressors and turbines of jet engines, fans and blowers. Flow over an aerodynamic surface has to be attached at higher angles of attack such that it increases the operational efficiency of flight vehicles. The primary goal of the aviation field in twenty first century is to develop the greener technologies and it can be achieved by advanced structural materials, efficient propulsion systems, and most importantly through enhanced aerodynamic efficiency. The presented review paper provides deep insights of various passive and active flow control techniques which are mainly associated with the enhancement of aerodynamic efficiency at different flight missions.



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I. INTRODUCTION

Fluid dynamics is a discipline which characterizes the flow of fluids, and illustrates the peculiarity on wide range of applications through aerodynamics and hydrodynamics. Contemplation of fluid dynamics at varying complexities triggers analysts to compensate ideas at difficulties and several innovations. Flow characteristics over the surface differ based on the size and shape of the solid objects. Generally, streamline body and bluff body are identified as a primary classification among the shape of the objects. When the drag is dominated by pressure drag, the body is streamlined and when it is dominated by friction drag, the body is classified as bluff body. The net force acts upwards on the airfoil when the pressure on the suction side is lower than the pressure side (lower surface). The possessions and the properties of viscosity supremacy to the formation of starting vortex, in turn it is accountable for bearing the capable circumstances for lift. Another aerodynamic force called as drag which plays a vital role in determining the object's aerodynamic performance. In the aviation history, numerous efforts have been executed to improve the lift with minimum drag for enhancing the performance characteristics of aircrafts. Particularly, the reduction of drag results in a substantial decrease of Specific Fuel Consumption (SFC). The summary of the flow control techniques discussed in this review are presented in Figure 1.

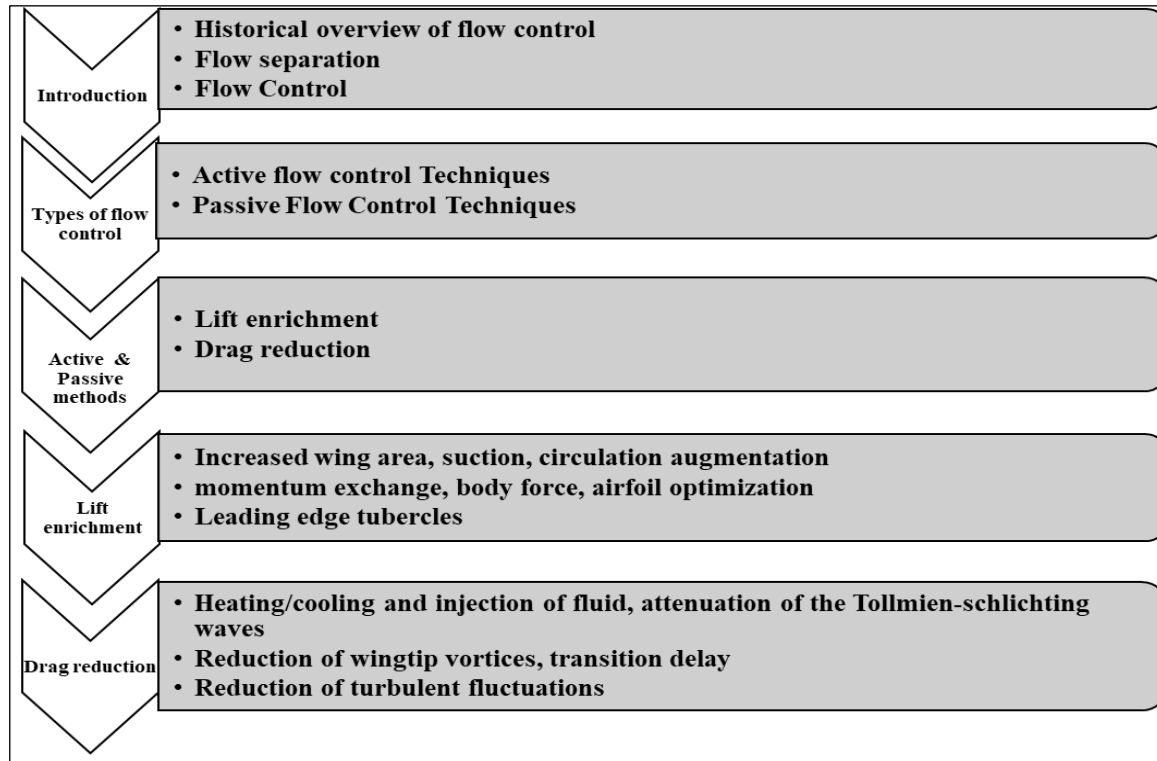


Figure 1: Content overview for various flow control mechanisms.

Source: Authors, (2026).

1.1 HISTORICAL OVERVIEW OF FLOW CONTROL

The dream of flying has curiosity to the human beings since earliest periods. The stories of wax wing with flight in Greek mythology, Ancient Egyptian god Khensu had wings have been a dream for man to fly. In 1903, first powered flight is accepted to have taken place by wright brothers, who inspired from Otto Lilienthal who made over 2000 successful glider flights [1]. Many research was focused on the use of ailerons which were developed in 1908 and use of slotted flaps on wing leading edge for lift enhancement [2]. In the late 1920, investigations on suction control towards boundary layer reattachment during flight condition were carried out [3]. The impact of world war-II induced research in to the development of aircrafts, missiles and ships with improved characteristics like fast, highly manoeuvrable and efficiency. It leads to focus on optimization of airfoil profiles with minimum thickness. This thin airfoil profile was benefitted with leading edge separation and encouraging the flow to reattach [4].

The appreciable experiments and achievements for flow control during 1940-1970 includes, bluff body splitter plates [5], vortex generators [6] helical strakes [7] and acoustic excitation [8]. During the period of 1970-1990, the research effort was focussed towards reduction of drag for commercial airlines, land vehicles, pipelines and other industrial devices. Also, usage of riblets and large-eddy break-up (LEBUs) devices were developed to reduce the skin friction in turbulent boundary layer [8]. Various active flow control methods were developed and employed in the mid of 1980's. Also, there was a transformation in flow control strategies, which is shifted to controlling flow instabilities from controlling the time-averaged state [9]. Recently, the development of actuators which is capable of controlling the flow at the timescale of instability has been strongly focussed. Zero net mass flux (ZNMF) jets, oscillating wire, morphing surface, magneto hydrodynamic devices are the examples of currently available actuators. However, the actuator bandwidth limitations and scaling issues still pose a significant problem for active flow control [10].

1.2 FLOW SEPARATION

The vorticity is ultimately cast at the trailing edge producing alternating sign in the wake. The circulation around the airfoil formed due to satisfy the conservation of angular momentum, there must be an equivalent motion to obstruct the vortex movement. By the form of circulation around the airfoil, the velocity vectors from the counter circulation add to the free flow velocity vectors that develop higher velocity above the airfoil and lower velocity below the airfoil that requires a pressure on above surface lower than the ambient pressure. Flow separation occurs when the boundary layer travels far enough against an adverse pressure gradient. As the severity of the adverse pressure gradient increases, the velocity profile becomes increasingly distorted and then becomes negative. The fluid becomes detached from the surface of the object, and instead takes the forms of eddies and vortices. Boundary layer separation is the detachment of a boundary layer from the surface into a broader wake. Boundary layer separation occurs when the portion of the boundary layer closest to the wall or leading-edge reverses in flow direction. The laminar or the transiting boundary layer which desirable to delay the location of separation.

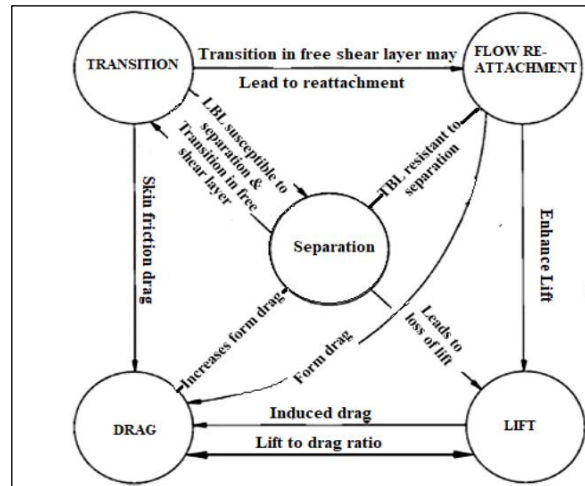


Figure 2: Effects of separation.

Source: [11].

Separation means for the flow detaches from the surface. Two types of separation are generally focused, one is weak separation and another is strong separation. Weak separation can be defined as that one where the separation point is variable or undefined. Weak separation occurs at streamline bodies, which is pressure drag dominated when compared to viscous drag. The separation increases when angle of attack increases. The strong separation case is one where the separation point is fixed. Mostly all bluff bodies with sharp corners occurring in strong separation which have more viscous drag when compared to pressure drag. It increases while velocity increases. For both the strong and weak separation cases, passive and active controls are possible. The detailed description about flow separation has been addressed by [11]. The flow separation is a very important phenomenon that is to be considered in air flow characteristics. The performance and stability of an airplane is often degraded by flow separation.

Flow separation takes place at different points on the upper surface of the airfoil depending upon the angle of attack. The point at which the flow separation takes place is called separation point. The flow separation is mostly induced by adverse pressure gradient. This flow separation is the main factor for drag formation in wing profiles. For an example, for an airplane wing profile, the total drag can mainly divide into the skin friction drag, pressure drag and induced drag. The sum of skin friction and pressure drag is called profile or form drag. Induced drag is related to lift production. If the speed is approached to sonic limit, a new component of drag will come into the account, known as wave drag. Reduction of overall drag is not an easy task and more complicated. While the drag of the wing is a key parameter to the performance, it should be agreed that the lift production is also important. So, the flow control is involved with lift enhancement and drag reduction.

I.3 FLOW CONTROL

The idea that has been developed to manipulating a flow field in order to achieve a specific design perspective through some function of actuation or desired change in flow behavior is the underlying principle of flow control. The following sections will be focus on manipulating of development of external wall bounded flow on the airfoil surface. Flow control is the technology that has been associated to manipulate the boundary layer over the surface. The non-dimensional parameter Reynolds number is an important factor to consider in the context of flow control. Reynolds number defines the type of boundary layer, whether it is laminar, transitional or turbulent. Depends on the boundary layer thickness, it is desirable to delay the separation location in order to increase the lift and reduction in skin friction drag

II. TYPES OF FLOW CONTROL

The word control seems too strict in the sense that the flow is just to behave in a given form. An adequate introduction and historical perspective of flow control have been addressed in the previous chapters. Flow control devices are generally designed to reduce the drag of a wing configuration. Some of the flow control devices are exclusively designed for increase the lift production rather than reduce the drag. However, they often lead to reduce the drag. The flow control devices will be classified into two groups; active and passive. The energy expenditure is the key parameter which will cause the main difference and make the type of device to consider for the purpose. The active control devices differ from the passive control in the sense that auxiliary/supplementary power is required. If the device requires no control power input, then it is typed as passive control. By the capability of switching on and off, active flow control techniques provide various performance advantages over passive flow control. By the peculiarity of active flow control, it possesses greater adaptability to changing flight conditions, capability to target specific instabilities and lower associated drag. Over passive flow control, the utilization of active flow control is complicated and less cost effective. Active flow control devices are complicated to design and need a greater level of maintenance than passive type devices. By virtue of its geometry, the passive flow control device alters the flow physics without input. Lift enhancement and drag reduction were the useful classification on designation of flow control. The generation of lift by an airfoil considered on alteration of shape, its orientation relative to the flow can be changed, tip stall can be minimized or degree of flow attachment and circulation can be enhanced. Hence, lift can be increased by wing area, angle of attack, camber, augmentation of circulation and momentum exchange in the boundary layer. The flow control methods focus on drag reduction by avoiding/delaying flow separation, reducing spanwise flow, avoiding/delaying transition to turbulence and reducing coherence of turbulent structures.

III. ACTIVE FLOW CONTROL TECHNIQUES

III.1 LIFT ENRICHMENT

III.1.1 Increased Wing Area/Camber

The amount of lift generated by a wing depends on the shape of the airfoil, wing area and the velocity of an aircraft. To generate more amount of lift during take-off and landing, leading edge slots and trailing edge flaps are used as shown in Figure 3. Both provide increment in camber and wing area when it is angled down. Deployment of spanwise slots creates a gap called slot which further improves performance.



Figure 3: Leading edge slot and trailing edge flap.

Source: Authors, (2026).

An alternative device to slat is a Krueger flaps as shown in Figure 4. These flaps are mounted on the bottom surface of the wing are hinged at their leading edge. When actuators extend the flap down position thus increasing the wing camber and do not have associated slot, which leads to inferior performance than slats [12].

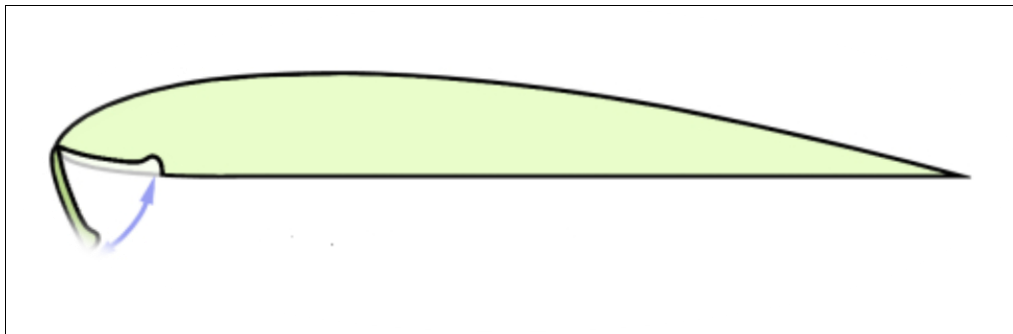


Figure 4: Krueger flap.

Source: Authors, (2026).

III.1.2 Suction

Suction can be used to stabilize a laminar boundary layer, delaying the transition of boundary layer and thereby reducing skin friction drag. This suction can be achieved by hybrid laminar flow control surfaces. It is an active drag reduction technique. The delay in transition of boundary layer from laminar to turbulent flow is generally achieved by the application of suction over the 10 to 20% of the chord. This method involves removing a small amount of the boundary layer fluid through a porous surface or a series of spanwise slots [12].

III.1.3. Circulation Augmentation

The primary purpose of this flow control technique is to allow lift generation at higher angle of attack and reduced pressure drag. A flat plate placed at the trailing edge of an airfoil perpendicular to the pressure side of the airfoil is called Gurney flap as shown in Figure 5. Its length is approximately 1% to 2% of the airfoil chord and this configuration gives both increased lift and reduced drag [13]. Increase the trailing edge suction due to vortex shedding process and deceleration of the flow at the trailing edge on pressure side jointly improves the overall circulation associated with a given airfoil [14].

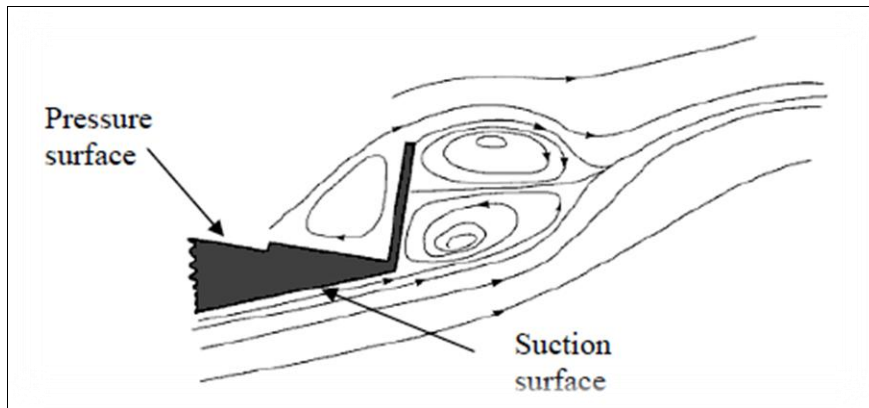


Figure 5: Gurney flap showing twin vortex flow field.
Source: [15].

Micro electro mechanical (MEM) translational tabs (microtabs) are active flow control devices on aerodynamics surfaces for lift enhancement. They are located slightly forward of the trailing edge of airfoil pressure surface. It creates a pressure side vortex and shifting the separation point from trailing edge to the end of the tab and changing the kutta condition, leading to an effective increase in camber [16].

III.1.4 Momentum Exchange/ Flow Separation Delay

Zero Net Mass Flux jets (ZNMF), slots and vortex generator jets enhance the momentum exchange and thereby delaying the stall. ZNMF jets or synthetic jets (Figure 6) are a compact actuator, no requirement for external air supply, more cost-effective alternative of flow separation control than the steady blowing and suction. ZNMF jets are cavities with membranes at the bottom. The membranes oscillate, drawing fluid into the cavity before expelling it. ZNMF jets promote increased mixing and give rise to a higher entrainment rate in boundary layer. In addition, streamlines are deflected from the surface which reduces the local upstream pressure gradient, thus lowering forces which lead to boundary layer separation. These characteristics substantially delay the stall and enabling the airfoil to generate a larger amount of lift with reduced pressure drag [17].

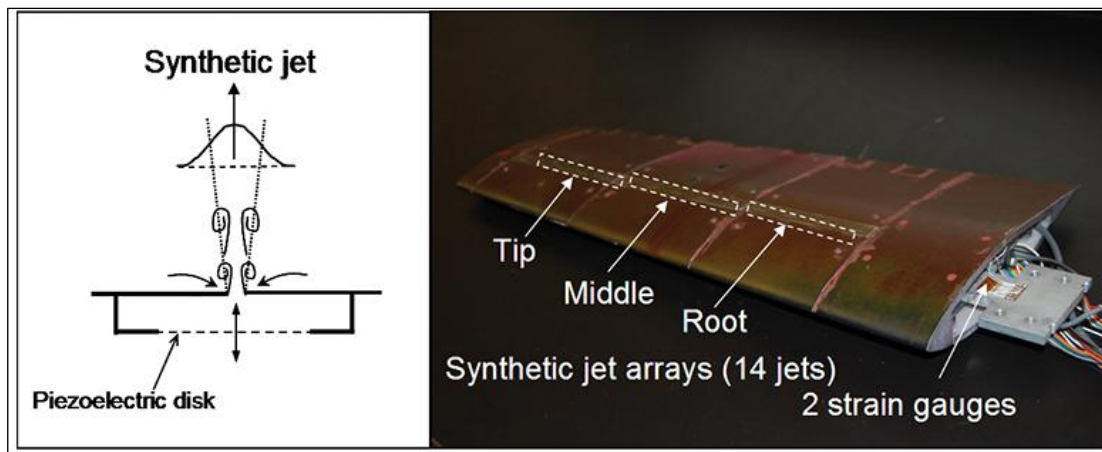


Figure 6: Synthetic jet schematic diagram on wind turbine blade model.
Source: [18].

Positioning of synthetic jet in the leading edge of the wing effectively increases the influence of asymmetric vortex on lateral directional stability and the control. The periodic injection leads to the control of asymmetric vortex improves the adverse pressure gradients resistance of main vortex to influence the asymmetric vortex. By the induction of synthetic jet control left and right separation vortices are effectively controlled [18]. A rectangular square tipped wing is examined experimentally for the development and control of Vortex under the effect synthetic jet active control. The induction of synthetic -jet control effectively curb the peak circumferential velocity and core axial velocity through maintaining the turbulent structure core. This actuated mixing in the inner region of vortex resulted increased mixing and subsequent diffused vortex [19]. The numerical investigation to study the effect of active flow control on NASA helicopter main rotor blade to improve the retreating blade stall. The flow control is achieved by using blowing jets at the leading edge of the airfoil that is used at the tip part of the main rotor blade. The results shows that this technique delays the flow separation by 10 % and incremental of lift about 40 %. This process of retreating blade stall also delayed in the forward flight [20]. Dual channel jet shows improved aerodynamic performances characteristics over the single jet channel on the wind turbine airfoil. Dual jet combined from the suction jet from the upper surface of airfoil and injection slot adjacent to the trailing edge, which enhances the leading-edge suction. It's evident that single jet channel did not control the boundary layer separation but double -jet channel helps the formation of boundary layer fully. This formation helps the production of lift by 84.21 % increment compared to the clean airfoil [21].

Slots are the spanwise gap, created when leading edge slats are deployed as shown in Figure 7. It allows the flow to be guided from the lower side of the airfoil to suction side, thereby increasing momentum exchange on the suction surface. During flight cruise conditions, slots remain closed but at higher angle of attack they are opened to enable higher lift generation.

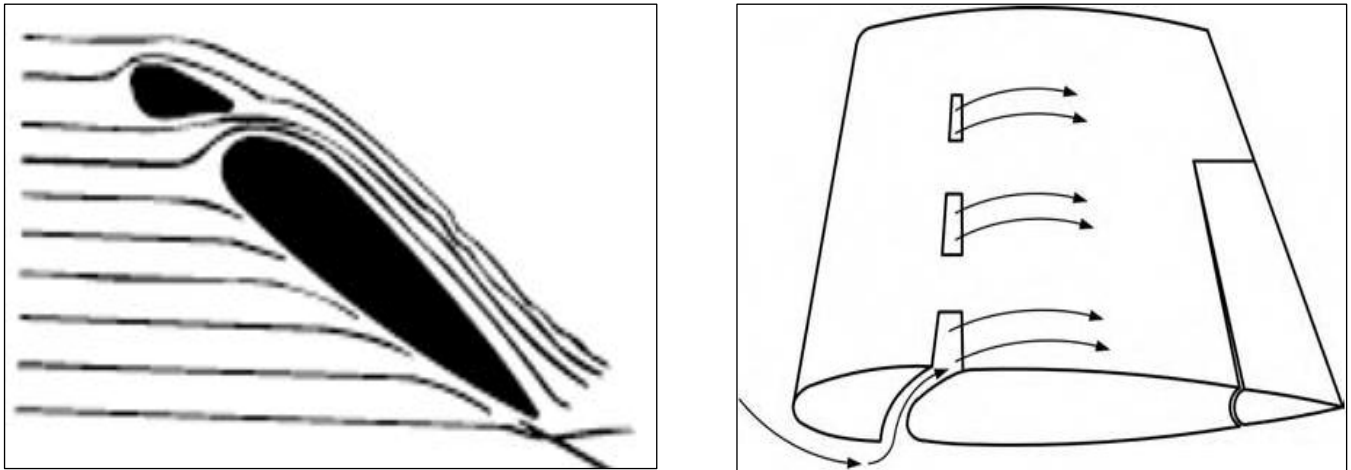


Figure 7: Leading edge slots.
Source: Authors, (2026).

Vortex generator jets enhance momentum exchange in a similar manner to traditional vortex generators, however they are more controllable and less intrusive [22]. They are oriented at a certain pitch and yaw angle and positioned near the separation point on the suction surface of an airfoil.

III.1.5 Application of Body Force to Air

Plasma vortex generator is based on Dielectric-Barrier-Discharge (DBD) mechanism. They are widely for both external and internal flow control applications including airfoil leading edge separation control, turbulent boundary layer control and lift augmentation. A DBD type plasma vortex generator consists of two electrodes on either side of a dielectric material. By applying a sufficiently high AC voltage across the electrodes, it causes surrounding gas to ionize and resulting into plasma [23]. This plasma produces an electrohydrodynamic body force on the ambient air that imparts momentum, which will produce vortices. In wing section, DBD plasma vortex generator is placed to the oncoming flow and produces stream wise vortices which will help to reattachment of flow. Unmanned Aerial Vehicles (UAV) equipped with plasma has been successfully control the flow separation with high voltage generator and plasma actuators. Main disadvantage of this technique is the requirement of high voltage which is associated with energy loss and increased weight [24].

The new active flow control technique in the axial compressor cascade with tip clearance is investigated experimentally by using hole- type bleed. The position of hole-type bleed plays an important role in controlling tip leakage vortex and passage vortex with incremental percentage of 8.34 % by delayed vortex origination. So that the performance benefit obtained in the compressor cascade [25]. A novel method of effectively distributing electromagnetic force periodically on the surface of the blended wing body -underwater glider helps in controlling the boundary layer structure is been studied numerically to understand the capability. The results show that equipping electromagnetic as an active flow control increases the lift production by 11.22 % [26]. In addition, Steady stream active flow control (SS- AFC) technique is analysed by the same authors and the methos is able to maintain the boundary structure in the blended wing body- underwater glider (BWB-UG). The steady suction AFC increases the aerodynamic characteristics of BWB-UG and its evident through by 45 % increment in lift to drag ratio

III.2 DRAG REDUCTION

In the active flow control techniques, an effective method for controlling the boundary layer involves mainly changing the near-wall viscosity through wall heating/cooling and injection of fluid having a different viscosity. Reduction of local fluid velocity has the influence of creating a fuller velocity profile which is more stable. Hence, cooling in air, heating in air or injection of lower viscosity fluids can obtain substantial transition delay of boundary layer and decrease the skin friction drag [27]. The next method is attenuation of the Tollmien-schlichting waves by surface heating at the leading edge of the body. This wave is a streamwise unstable wave which arise in a bounded shear flow. Tollmien-schlichting waves attenuation can be used to delay the boundary layer transition [28]. Surface heating in adverse pressure gradient regions may speed up the boundary layer transition which may be desirable when boundary layer trip is required. The convenient of surface wall heating or cooling as a flow control technique is limited by heat source size.

IV. PASSIVE FLOW CONTROL TECHNIQUES

Passive type flow control methods generally improve the condition of flight vehicles by manipulating the flow properties in the boundary layer. The flow manipulation is an efficient way to control the mixing in the separated shear layer. Optimization of airfoil profile, circulation augmentation by blown flap, momentum exchange, and separation delay by vortex generators, leading edge serration, turbulators, wing fences, winglets and placement of longitudinal grooves or riblets are the appreciable passive flow control techniques. These methods are described in the following section have been categorized according to their predominant mechanism.

IV.1 LIFT ENRICHMENT

IV.1.1 Optimization of Airfoil Profile

To optimize the actual airfoil profile to improve the lift and reduce the drag, the angle of attack, Reynolds number, operating range must be considered. Generally, for a given angle of attack and span, a wing will produce more lift if an airfoil has increased camber and chord length. In addition, if the flow remains well attached over the surface, it will be benefitted to reduce the skin friction drag and keep the flow as laminar as possible. This can be achieved by designing the airfoil profile with maximum thickness location as far aft as possible [29]. The presence of an appropriate design cavity on the suction side of the airfoil is called trapped vortex cavity as shown in Figure 8. This is also an important airfoil profile optimization which is able to trap a vortex inside and enhanced shear layer influencing the flow reattachment.

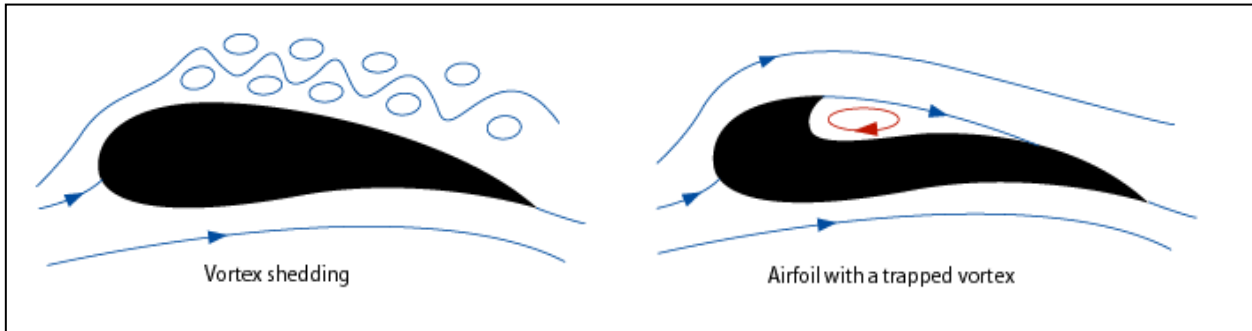


Figure 8: Trapped vortex cavity.
Source: Authors, (2026).

A novel flow control idea, which permits to oversee bluff-body wake dynamics and the laminar–turbulent transition is introduced by [30] by using Large-eddy simulations (LES). Result shows that, the bluff- body which control behavior of the boundary layers and lift to drag ratio increased from 1 to 1.5 %.

IV.1.2 Circulation Augmentation

Jet exhaust from the engine of an aircraft is directed over the wing surface is an alternative to flaps or to enhance their effectiveness by circulation augmentation concept. The exhaust jet is attracted to the curved surface of the wing that required preventing the boundary layer separation and keeping the flow attached at higher angle of attack. This effect is called Coanda effect. Increase of circulation occurs if the amount of air blown over the surface of the wing is greater than the amount required to keep the flow attached which results in an increased lift production [31]. In Gas Turbines, to avoid the combustion instability, the compressor blades are overworked to maintain the pressure ratio. Flow control techniques can be used to improve diffusion ratio for various operating conditions. A novel techniques Adaptive Coanda jet control (ACJC) is introduced to enhance the compressor stator cascade diffusion ratio and optimize the mass flow ratio by 1.2 to 1.2 % and by reducing the pressure loss ratio by 18.88 % to 21.53 % for the Mach number range between 0.1 to 0.4 [32].

IV.1.3.Momentum Exchange / Separation Delay

Vortex generator is an aerodynamic surface, consist of small vanes in rectangular or delta shaped creates a vortex. These devices run in spanwise lines near the thickest part of the wing and conventionally have a height which corresponds to the thickness of the boundary layer. Vortex generator protrudes above the boundary layer and have discontinuities that create either co-rotating or counter rotating stream wise vortices as illustrated in Figure 9, depending on device orientation. The generated vortices which draw energetic, made the momentum exchange in the boundary layer or reenergizing the boundary layer to delay the separation and stall [33], [34]. A wide-ranging passive flow control devices were considered to understand the effectiveness in separation control [35-37]. It has been determined that vortex generators were more efficient in achieving the flow separation control by means of the stream wise vortices produced on them. The VGs producing counter rotating stream wise vortices are much more efficient than that of producing co-rotating stream wise vortices.

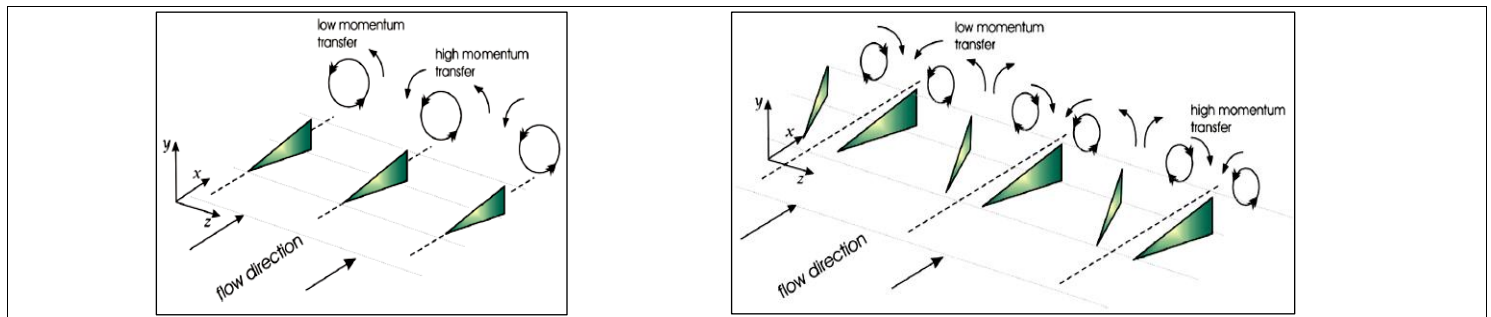


Figure 9: Co-rotating and counter rotating vortex generator.
Source: [34].

Another method of generating counter rotating streamwise vortices on the suction surface of an airfoil is leading edge serration. These leading-edge serrations are comb-like structures. Counter rotating vortices pairs was formed over each serration which essentially modified the flow in the suction surface and mitigated the flow separation properties with increasing angle of attack. Performance improvements of serration are depending on position of serration as close as possible in front of stagnation point, size and spacing [38]. Similarly, the dye flow visualization analysis of aircraft wing leading edge strakes shows the generation of high-swirl vortex at higher angle of attack [39], [40]. This vortex will help the flow to attach over the top surface of the wing. The penalty associated with this vortex is vortex bursting which leads to structural damage at the tail section [41]. The effect of passive flow control by using vortex generators were analyzed numerically and the streamlines pattern shows that the attached flow is possible over the surface of NACA0012 aerofoil at higher Angle of Attack [42]. Through tripping a laminar boundary layer to turbulent, momentum exchange can be enhanced. This can be achieved by turbulator. They are typically spanwise thin raised strips as depicted in Figure 10. Turbulators may also be created using distributed roughness elements. Accelerating the onset of transition is benefitted at increased angle of attack, as it facilitates a greater mixing of momentum with the free stream, which delays separation [43]. This ultimately results in the wing producing more lift and less drag. The height and position of turbulators are important parameters to ensure their success.

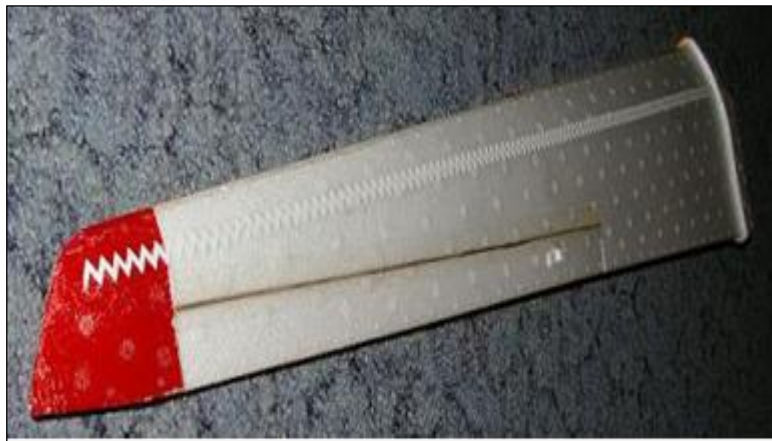


Figure 10: Wing with zig-zag turbulator along the entire span.
Source: Authors, (2026).

Separation delay can also be realized when the pressure gradient at the surface of an airfoil are altered. This occurs when a rippled trailing edge is incorporated into the airfoil. In this case, the undulations are perpendicular to both the free stream flow and the airfoil chord. Another interesting method of separation delay was inspired by the observation that when birds land the covering feathers on the suction surface of their wing rise up. Same design was tested where movable metal flaps were attached to the airfoil's suction surface and could pivot to a limited angle [44]. The flaps were located close to the trailing edge and create a physical barrier to further flow movement towards the leading edge. A ring-based Karman- vortex generator (KVG) is designed to position in the conical diffuser. This KVG is positioned in various locations for controlling the formation of vortex. The effectiveness of KVG is demonstrated in the wake near wall region. This enhances the flow mixing which promotes the delaying in flow separation in the downstream section [45], [46]. Passive shock wave/boundary layer control (PSBC) for drag reduction was conducted by SC(2)-0714 supercritical wing, with emphases on parameter of porous/slot and bump, such as porous distribution, hole diameter, cavity depth, porous direction at Mach number of 0.2 [47]. The computational and experimental study to understand how unsteady jet actuators are helping in drag reduction of heavy truck model by improving the control efficiency. This unsteady jet actuators improves energy efficiency up to 94.74 % for the small truck model [48].

IV.1.4. Restriction of Spanwise Flow

Swept wing profiles are subjected due to their geometry, to spanwise flow. This spanwise flow contributes to a higher wing loading towards the wingtip region than the inner portions of the wing and subsequently increases the induced drag. This is undesirable because it results in a thicker boundary layer in a tip region, which causes the wingtips to stall at lower angle of attack, reducing the wing's stability and reduced effectiveness of the boundary layer [49]. Wing fences are flat plates fixed normal to the suction surface of the airfoil that run in the chordwise direction, parallel to the flow direction. It is a physical barrier to hinder spanwise flow along the wing and shifting the lift distribution toward wing root, which consequently decreases drag and increases stability. Vortex generators, saw tooth leading edge, notched leading edge are the other methods for spanwise flow control [50].

IV.2 LIFT ENRICHMENT

IV.2.1 Reduction of Wing Tip Vortex

Wing tip vortices are circular/curl patterns of rotating air left behind the wing due to pressure variation on upper and lower surface of the wing. It will induce the main component of drag. The winglet design is mainly used to reduce the induced drag of a wing while it produces the lift. Winglets reduce the strength of the wingtip trailing vortex and induce the secondary flow results in reduction of induced drag as shown in Figure 11.

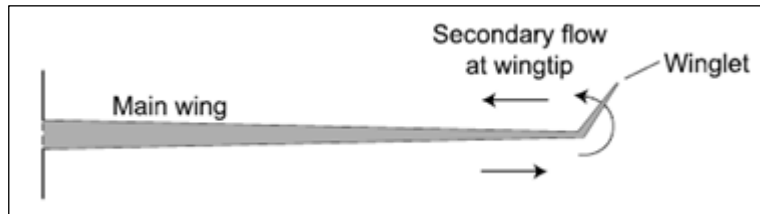


Figure 11: Secondary flow around wing tip.

Source: [15].

Another method to reduce the induced drag is wing planform optimization. For an example, a high aspect ratio wing tends to have a relatively low induced drag but offers lower maneuverability. Planar and non-planar wings may result in the reduction of induced drag due to different span efficiency factors. While a wing with elliptical distribution achieves the maximum theoretical planar span efficiency of 1, the non-planar wing planforms achieve span efficiency factor up to 1.46 [51].

IV.2.2 Transition Delay

To delay the boundary layer transition and to reduce skin friction drag through interaction with instability modes such as Tollmien-Schlichting instabilities, static divergence and well known passive compliant coating can be used. This passive compliant coating present a much simpler alternative to reactive control strategies aimed at favorably interfering with wall bounded flows. Suppression of a given instability mode can lead to transition delay and hence skin friction reduction, provided other modes do not grow in response to the fluid structure interaction [52]. The passive bleeding achieved by allowing the wind flows through the wing passage from the pressure side to suction side, this method is an effective flow control method in non-slender delta wings. This approach eradicates the surface separation and it increases the surface normal vorticity and suction pressure co-efficient. Particle Image Velocimetry (PIV) measurements shows that, the effective bleeding improves the stall and lift co-efficient [53].

IV.2.3 Reduction of Turbulent Fluctuations

The viscous drag of the turbulent boundary layer is a significant factor contributing to the fuel cost of the airlines. Several investigations have indicated that micro surface geometry variations which are able to change the near wall structure of the flow have been effective in drag reduction. A moderately effective way of reducing turbulent skin friction involves surface modification in the form of riblets. It consists of minute streamwise ridges and valleys as depicted in Figure 12. They obstruct the fluctuating turbulent cross flow close to the wall. This leads to reduction in momentum exchange and hence reduces the skin friction drag. The optimum non dimensional, spanwise spacing between riblets has been described in wall units.

$$s^+ = s \sqrt{\tau_w / \nu} = 10 - 20 \quad (1)$$

Where,

= spanwise spacing

= wall shear stress

= kinematic viscosity

The corresponding actual spacing for flight condition is 25 to 75 . Polymeric riblet film is currently being used on regular commercial flights of A 340-300 aircrafts, which has been observed that 5 % to 8% skin friction drag reduction [54].

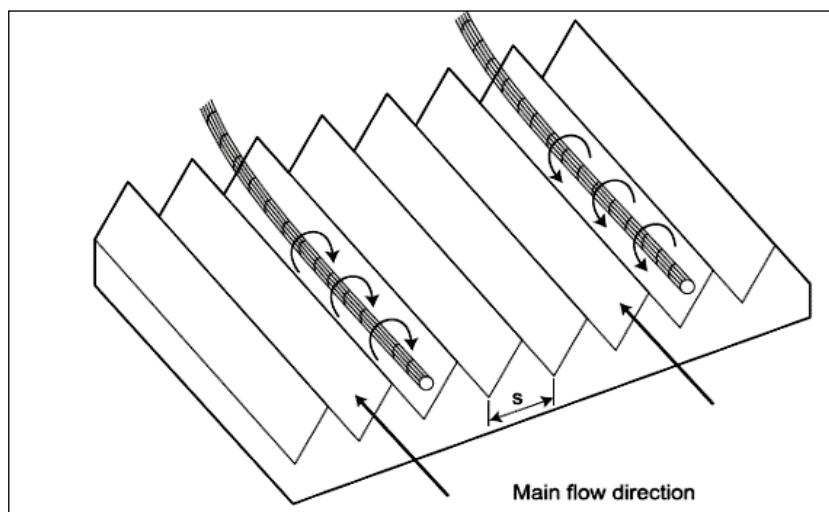


Figure 12: Effect of riblets with near wall structure.

Source: Authors, (2026).

Large-Eddy-Break Up (LEBU) devices are thin short plates or airfoils are mounted in the outer part of boundary layer and can be able to change the near wall velocity fluctuations and turbulent structure. This is achieved when the trailing edge vortices shed by the short thin plates cancels the incident vortices effect. Hence, these devices reduce the amount of drag. The thickness of the plate and adequate structural rigidity are the important parameters for high-speed flows [55].

V. FLOW CONTROL & STALL DELAY THROUGH BIO-INSPIRED TECHNOLOGY

Bio-inspiration or Biomimetic refers to human-made processes, substances, devices or systems that imitate nature. Recent studies have increasingly focused on flow control methods inspired by biology, as well as techniques used by living organisms. Understanding these bioinspired and biological flow control methods is beneficial in two key ways. First, they provide valuable insights into how biological creatures move efficiently and adapt to various flight conditions, revealing the underlying physics. Second, bioinspired flow control techniques are more appropriate for small uncrewed vehicles than conventional methods, which are typically designed for larger, high-speed operations. The small size and limited payload capacity of these vehicles make traditional flow control systems impractical due to their size, complexity, and weight [56]. Additionally, scaling down conventional devices may not meet the specific needs of small vehicles. Traditional flow control methods are effective only within a narrow range of angles of attack and operating conditions, whereas small uncrewed aerial or aquatic vehicles (sUAVs) often need to perform across a broader range. Because the operating environments of these vehicles share similarities with those of biological organisms, bioinspired flow control techniques offer an ideal solution to enhance sUAV performance [57].

V.1 TUBERCLES

One among the observable evolution, the Humpback whale (Figure 13) intended among the numerous marine mammals in the designs of airfoil [58]. Among the blue whale family, humpback whale notable for its tight turning manoeuvres caught to considered for its flipper composition, tracing tubercles as the critical criteria for the advancement of airfoil. Tubercles are the leading-edge protuberances and the presence of tubercles on the leading edge of airfoil increases the momentum exchange in boundary layer, which leads to separation delay. In addition, extend of spanwise flow reduced by tubercle's streamwise vortices [59].

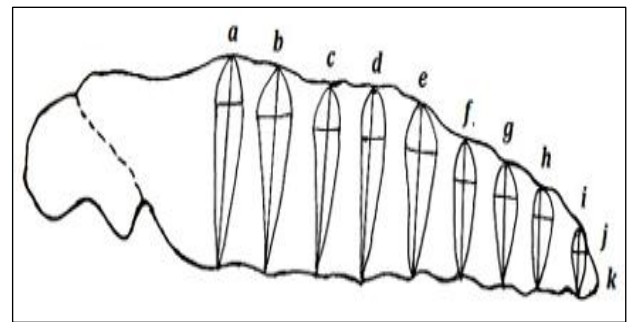


Figure 13: Humpback whale flipper & Flipper planform view.

Source: [58].

The biomimetic flow control techniques are addressed with their potential applications in relevance to the aerospace industry. The category of plants, insects, birds and aquatic animals are considered with their potential towards aerodynamic efficiency parameters such as lift enhancement and drag reduction. Super hydrophobic surfaces Lubricated surfaces Grooved circumference Winged seeds, Spade like protrusions Corrugated Airfoil Hind-wing tail, Leading edge serrations Riblets, Wing tip feathers, Biomimetic fish scale arrays, Leading edge tubercles are the unique designs identified for biomimetic flow control techniques. The implementation of bioinspired HW LE tubercles on airplane wing LE has demonstrated significant benefits because of its flow control characteristics. In the view of aerodynamic performance improvements of flight vehicles, the tubercles make an ample avenue for new engineering design of wings, hydrofoils and control surfaces with the meagre influence of aeroelastic effects [60].

V.2 AVIAN FLOW CONTROL

Bird wings are equipped with various groups of feathers that fulfill several roles, including providing insulation to regulate body temperature, enhancing flight efficiency, and reducing noise. In terms of aerodynamics, beyond creating the required forces for flight, feathers also function as devices that manage airflow [61], [62].

V.3 COVERT FEATHERS

The covert feathers are a type of contour feathers found on both the upper and lower surfaces of birds' wings and tails. Wing coverts are arranged in several overlapping layers, with the row closest to the leading edge called the lesser coverts, followed by the median coverts and the greater coverts [63]. Gaining insight into the role of these coverts in controlling airflow during bird flight has been essential in designing bio-inspired flow control devices [64].

V.4 LEADING EDGE SERRATIONS

Leading edge serrations (LES) are comb-like hook structures found on the outer vanes of feathers at the front edge of the wing, while trailing edge fringes are defined by separated barbs at the feather tips.

These features have been widely studied for their ability to reduce noise and enable silent flight, particularly in owls. However, as this article focuses on flow control rather than noise reduction, we will emphasize the studies examining the role of LES in aerodynamic optimization. In addition to their noise-reduction properties, LES act as flow control devices by enhancing aerodynamic efficiency and facilitating the transition from laminar to turbulent flow [15], [65].

Table 1: Flow control techniques and their corresponding effects and advantages.

Passive and Active flow control techniques	Effect on flow	Aerodynamic Advantages
• Tubercles • Vortex generators • Leading edge serrations • Rippled trailing edge • Moveable flaps • Slots • Suction • Vortex generator jets • Plasma	Delayed separation.	Increased lift/stall angle, possible drag reduction.
• Flaps • slats • leading edge flaps	Increased velocity on Suction surface.	Increased lift/stall Angle.
• Blown flaps • Gurney flap	Circulation augmentation.	Increased lift/stall Angle.
• Tubercles • Wing fences • Saw tooth leading edge • Notched leading edge • Vortex generators	Restricted span wise flow.	Avoidance of tip stall and stall delay
• Turbulator • Manipulation of near-wall viscosity.	Accelerated transition.	Delaying of stall.
• Shape optimization • Compliant Coatings • Suction • Manipulation of near wall viscosity	Delayed boundary layer transition	Reduced skin friction drag
• Riblets, • Large-eddy break up devices	Reduced momentum Exchange	Reduced skin friction drag
• Winglets • Wing planform optimization	Reduced wingtip vortices	Reduction in induced drag

Source: Authors, (2026).

VI. CONCLUSION

The widespread passive and active flow control techniques used for various aerospace applications with the implementation challenges are focused in this comprehensive review article. As the modern aerodynamics is highly influenced by the Bio-inspired designs to optimize the aerodynamic drag, passive flow control mechanism has received greater attention in the past decade. In this, the crucial objective is to establish a relevant circumstance for tubercles, which is a passive method to improve the boundary layer momentum exchange. Vortex generators, leading edge serrations, and ZNMF jets were also identified for this boundary layer momentum exchange, however it provides further detailed description for alternative designs. Meanwhile, these additional features have been proposed as contributing parameters to performance improvement for airfoil with tubercles. The progress and challenges of flow control methods explained in this article should be considered with aerodynamic benefits in addition to the cost analysis. Several other methods are not addressed in this article because of their potential drawbacks associated with the complex instrumentation and technical feasibility. Further, remarkable information is that several passive techniques such as compliant coating, vortex generator, micro tabs, and adaptive wings have been tripped in to active form in the recent times.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: V. T. Gopinathan, R.Saravanan and M.Ganesh.

Methodology: V. T. Gopinathan, R.Saravanan and M.Ganesh.

Investigation: V. T. Gopinathan, R.Saravanan and M.Ganesh.

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