An Integrated Study of Airfoil Aerodynamic Performance Enhancements: A Review

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Abstract— **The aerodynamic performance of airfoils plays a pivotal role in optimizing efficiency and functionality across various engineering applications. This review synthesizes experimental, theoretical, and computational advancements to provide a comprehensive understanding of the mechanisms influencing lift and drag forces. The study explores airflow interactions with airfoil geometries, highlighting their significance in enhancing aerodynamic efficiency. Experimental approaches, including wind tunnel testing and flow visualization, are critically examined alongside theoretical frameworks such as lifting line theory and thin airfoil theory. Furthermore, state-of-the-art Computational Fluid Dynamics (CFD) methodologies are analyzed for their capability to simulate airflow patterns and predict performance under diverse conditions. By integrating insights from these multidisciplinary perspectives, this review establishes a robust knowledge base for advancing airfoil design and performance optimization. These findings are crucial for fostering innovations in aerospace engineering and related fields.**

Keywords—Airfoil, Aerodynamic efficiency, Angle of Attack, Coefficient of lift, Coefficient of drag

I. INTRODUCTION

Airfoils play a crucial role in various engineering applications, from aircraft to wind turbines, where their aerodynamic performance directly impacts efficiency and functionality. Over the years, extensive research has been conducted to enhance airfoil designs and optimize their performance. The wind tunnel study conducted by Oxford and the Air Force Institute of Technology [1], which investigated the effects of trailing edge modifications on the lift-drag ratio of circulation-controlled airfoils. This study laid the groundwork for understanding the impact of airfoil modifications on aerodynamic performance. Subsequent studies [2],[3],[4] such as the research by Bénard et al. [5], focused on utilizing plasma actuators to control lift and drag performances of axisymmetric airfoils, showcasing innovative approaches to aerodynamic manipulation. Advancements in computational fluid dynamics (CFD) have revolutionized airfoil analysis, enabling detailed simulations to optimize performance. The work by Siauw et al. [23] utilized fluidic vortex generators to study the transient dynamics of flow around a NACA 0015 airfoil, demonstrating the effectiveness of CFD in understanding complex flow phenomena. Similarly, Douvi and Margaris employed CFD simulations to investigate heavy rain flow over a NACA 0012 airfoil [16], highlighting the importance of environmental factors in airfoil performance.

Experimental studies, such as the evaluation of icing scaling on swept NACA 0012 airfoil models [15] by Tsao and Lee, have provided valuable insights into real-world challenges faced by airfoils. Additionally, research by Genç et al. and Bhat and Govardhan explored the aerodynamics of various NACA airfoil profiles at low Reynolds numbers [18], shedding light on fundamental flow characteristics and stall phenomena. These experimental investigations complement computational studies, offering validation and practical relevance to theoretical analyses. Recent research has focused on optimizing airfoil designs for specific applications, such as wind turbine blade design. Ismail and Vijayaraghavan [22] examined the effects of airfoil profile modification on vertical axis wind turbine performance, while Hossain et al. [21] conducted experimental studies on aerodynamic characteristics using dimpled airfoils. These studies demonstrate the interdisciplinary nature of airfoil research, incorporating aspects of fluid dynamics, materials science, and renewable energy.

Theoretical studies on airfoil aerodynamics have established foundational frameworks for understanding and predicting aerodynamic behavior [29],[30]. Analytical models like the lifting line theory and thin airfoil theory have elucidated mechanisms of lift and drag generation. These models are complemented by the application of the Navier-Stokes equations, offering insights into complex flow behaviors such as laminar-turbulent transition and flow separation. Researchers have further refined these theories by incorporating innovative approaches, such as morphing airfoil designs, passive flow control methods, and noise prediction algorithms [34],[35]. Such developments underscore the importance of theoretical analyses in advancing airfoil design, optimizing aerodynamic efficiency, and addressing phenomena like stall and boundary layer behavior[38],[42].

Computational studies, particularly using Computational Fluid Dynamics (CFD), have revolutionized airfoil research by providing detailed simulations of airflow and performance metrics under varying conditions [45],[48],[49]. These studies enable precise predictions of lift and drag coefficients, flow separation points, and transition dynamics. Advanced numerical approaches, such as Reynolds-Averaged Navier-Stokes (RANS), Large Eddy Simulation (LES), and Detached Eddy Simulation (DES), have been instrumental in optimizing airfoil shapes for improved aerodynamic efficiency. Applications range from investigating airfoil modifications like serrations and dimples to analyzing environmental factors such as icing and heavy rainfall [69],[72],[81]. By validating theoretical models and complementing experimental findings, computational methods have become indispensable in modern airfoil research and design.

This review aims to provide a comprehensive overview of the advancements in enhancing the aerodynamic performance of airfoils, incorporating both experimental and computational approaches. By analyzing a range of studies, including wind tunnel experiments, numerical simulations, and theoretical analyses, this review highlights key findings, methodologies, and trends in airfoil optimization.

II. EXPERIMENTAL STUDIES

Experimental studies in airfoil research have provided valuable insights into real-world aerodynamic challenges. These studies [11], [12], [13], [14] have focused on investigating the effects of various factors, such as trailing edge modifications, plasma actuators, and environmental conditions, on airfoil performance as shown in Table 1. Through wind tunnel tests and empirical analyses, researchers have gained a deeper understanding of lift-drag ratios, icing scaling, and stall phenomena in different airfoil profiles.

2.1 Profile Modification

Several studies have explored methods to improve lift coefficient and reduce flow separation on airfoils through modifications to the leading or trailing edge. S.M.A. Aftab and K.A. Ahmad investigated the impact of tubercles on the leading edge of a NACA 4412 airfoil, observing enhanced aerodynamic performance, particularly at high angles of attack. Their numerical and experimental analyses demonstrated reduced drag and increased lift coefficient as shown in Figure 1, offering potential benefits for flight maneuverability [1].

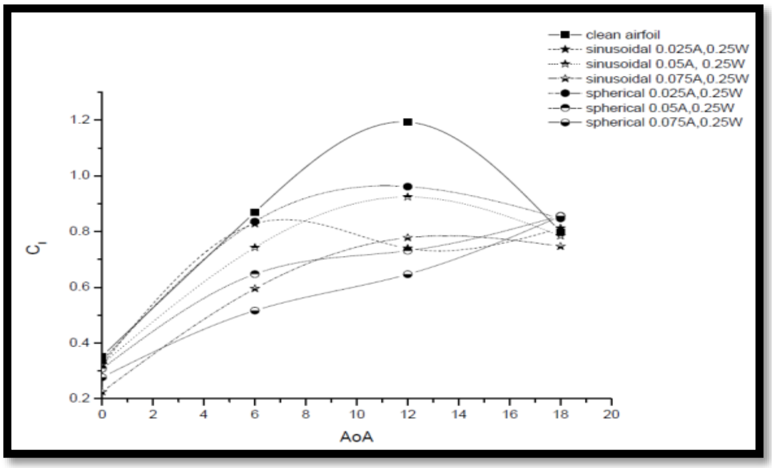

FIGURE 1 : CL VS. AOA[1]

Similarly, N. Rostamzadeh et al. found that wings with tubercles can mitigate flow separation, enhancing loading characteristics at elevated attack angle [2]. Expanding on this, Vamsidhar Katam's study introduced an adaptive actuator to modify the camber of a NACA 4415 airfoil dynamically, effectively managing flow separation given in Figure 2 and improving lift-to-drag ratio as shown in Figure 3 [3].

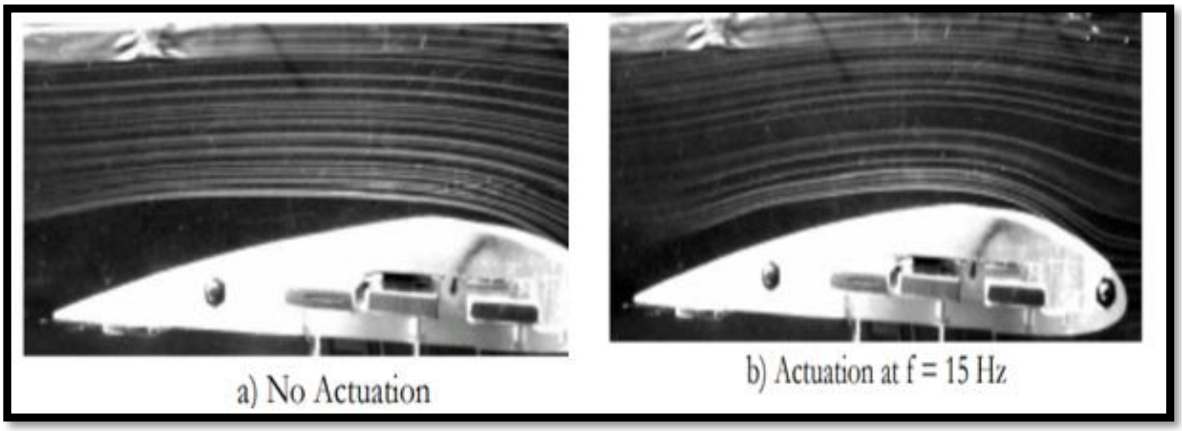

FIGURE 2 : STREAMLINES AT RE = 25,000 AND AOA = 0 DEGREE.[3]

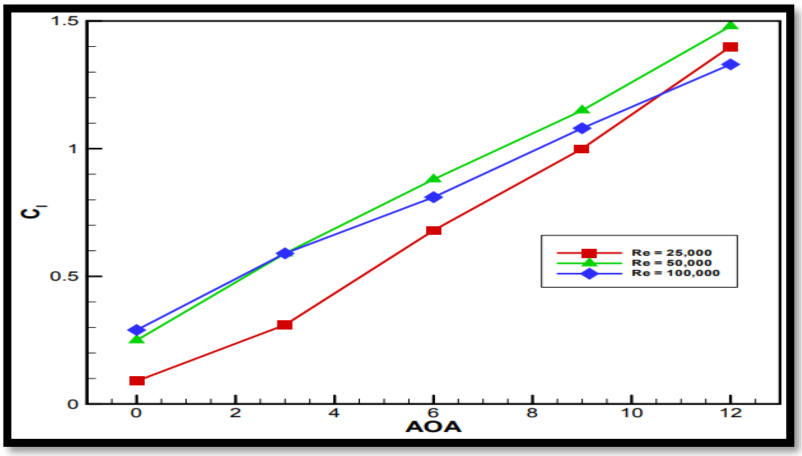

FIGURE 3: VARIATION OF CL WITH ANGLE OF ATTACK AT THREE DIFFERENT REYNOLDS NUMBERS [3]

Additionally, Douglas R. and Smith et al. employed synthetic jet actuators to study flow reattachment on a modified airfoil, effectively reattaching detached flow and improving aerodynamic performance as shown in Figure 4 [4]. Furthermore, S. Raghunathan and C. P. Tan investigated the impact of blade profile and thickness on turbine performance. Their study revealed that using thicker aerofoil sections and redesigned blade profiles can significantly enhance turbine starting torque and operating efficiency. These studies collectively underscore the importance of aerodynamic modifications in enhancing airfoil and turbine performance, offering insights into improved flight maneuverability and energy efficiency [5].

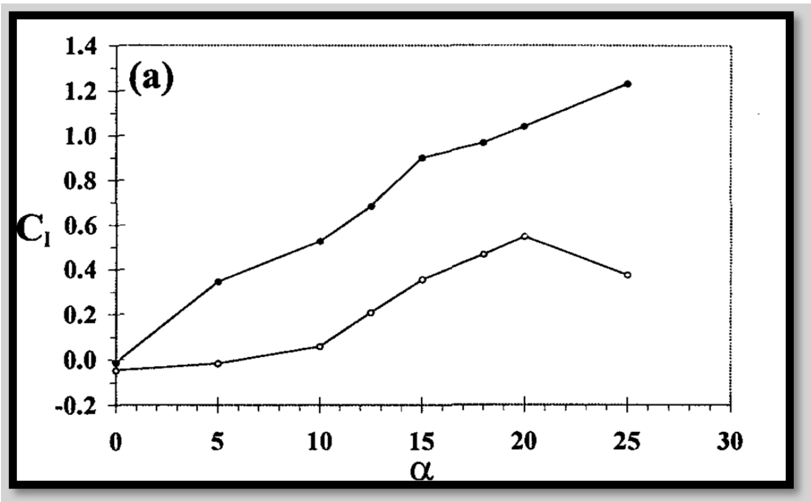

FIGURE 4 : CL VS. AOA [4]

Md. Abdullah et. al. conducted research on the NACA 4415 airfoil, focusing on modifying its geometry to enhance aerodynamic characteristics. Their wind tunnel experiments compared standard and modified wing models, with pressure measurements taken on both upper and lower surfaces to analyze lift coefficient variations. Introducing a step at 55% chord length with a backward-facing orientation significantly improved aerodynamic properties, increasing lift coefficient given in Figure 5 and lift-to-drag ratio [6]. Similarly, Livya Ethiraj and Subramania Nadaraja Pillai's explored aerodynamic enhancements through modifications to the NACA series airfoil, specifically the NACA 0020. The experimental analysis incorporated expanded trailing edges and triangular serrations, aiming to control flow patterns and delay stall phenomena. Results demonstrated increased lift coefficients and reduced drag, suggesting potential applications for smart airfoil design [7]. These studies collectively highlight the effectiveness of geometric modifications in improving airfoil performance, offering insights into enhancing aerodynamic efficiency and controlling flow behavior for future aerospace applications.

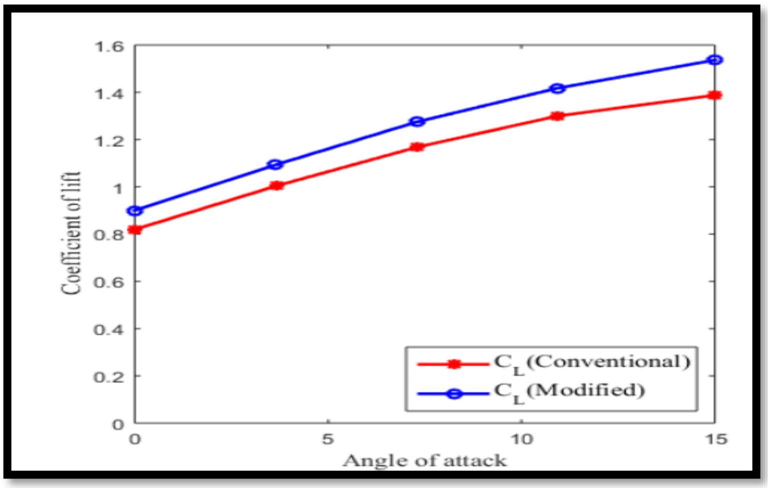

FIGURE 5: COEFFICIENT OF LIFT FOR BASE AND MODIFIED WING AT DIFFERENT ANGLE OF ATTACK [6]

Richard F. Jones et. al. conducted experiments to assess various airfoil shapes, aiming to identify designs that effectively minimize aerodynamic drag and noise. They discovered that operating at lower Reynolds numbers could increase drag but reduce noise for airfoils designed specifically for these conditions. Interestingly, they found that reductions in drag were not always accompanied by noise reductions. In some instances, the presence of a laminar separation bubble could worsen aerodynamic performance. However, the airfoil's pressure recovery section could thin the boundary layer at the trailing edge, thus reducing trailing edge boundary layer (TBL-TE) noise predictions. They achieved significant drag reduction and noise level decreases through drag-constrained shape optimization, focusing on the trailing edge slope and thickness [8]. Haci Sogukpinar explored how adjusting an airfoil's thickness could enhance the lift-to-drag ratio. His findings indicated that thinner airfoils experienced more rapid changes in the drag coefficient as a function of angle, demonstrating the importance of airfoil geometry in aerodynamic performance [9]. Building on these insights, Diksha Singh et. al. conducted a comprehensive study using a low-velocity wind tunnel to compare the performance of different airfoil shapes. Their experiments, covering a wide range of attack angles, showed that symmetrical airfoils significantly outperformed flat and cambered airfoils at lower angles of attack. However, at angles beyond 80 degrees, cambered airfoils exhibited superior performance. This body of research collectively underscores the nuanced relationship between airfoil shape, aerodynamic efficiency, and noise production, highlighting the potential for tailored designs to optimize specific performance metrics. While symmetrical airfoils excelled at lower angles of attack, cambered airfoils showed superior performance beyond 8 degrees of attack given in Figure 6. This comprehensive investigation, which involved 33 experiments across the three distinct airfoil shapes, concluded that symmetrical airfoils generally offer better performance, though flat airfoils can be more effective at higher critical angles [10].

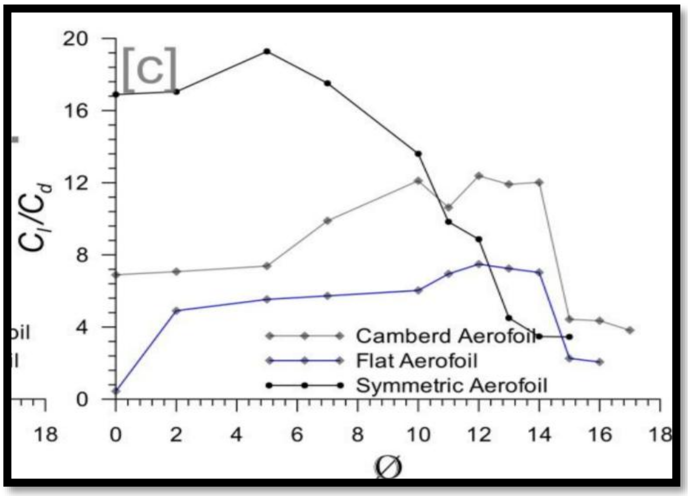

FIGURE 6: PERFORMANCE OF AEROFOIL WITH (Ø) OF THREE DIFFERENT SHAPE OF AEROFOIL [10]

The foundational work by A. Sherman on the NACA 4400R Series airfoils [11] laid a significant cornerstone in understanding and modifying airfoil characteristics for improved aerodynamic efficiency. Sherman's innovative approach to decreasing the pitching moment to -0.03 by implementing a reflex in the trailing edge marked a pioneering step in airfoil design, specifically targeting the NACA 4409B, 4412B, 4415B, and 4418B models. These modifications were critical in maintaining the core characteristics of the original 4400 series while optimizing performance up to the 40 percent chord station. Building upon Sherman's empirical findings further investigation into the effects of aspect ratios, airfoil thickness, and Reynolds numbers on the lift coefficient curve revealed nuanced insights into the aerodynamic performance, highlighting a reduction in lift with decreased aspect ratios at certain angles of attack. This research offered a deeper comprehension of the intricate interplay between airfoil geometry and aerodynamic efficiency, validating the foundational principles laid down by Sherman. Parallel advancements in the realm of airfoil optimization were made by Harris C.D and Blackwell J.A. Jr, [12] who explored the potential of rear upper surface modifications on the NASA supercritical airfoil. Their combined experimental and computational approach, spanning Mach numbers as shown in Figure 7 from 0.60 to 0.81, showcased the substantial impact of modifying upper surface curvature, particularly around the 50 percent chord station. This study not only confirmed the critical nature of surface geometry for aerodynamic performance but also introduced a sophisticated methodology for airfoil design and analysis.

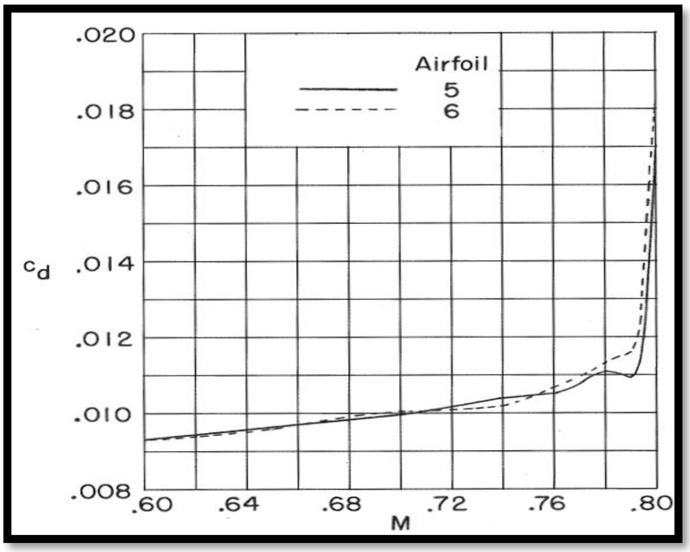

FIGURE 7 : VARIATION OF SECTION DRAG COEFFICIENT WITH MACH NUMBER AT THE DESIGN NORMAL-FORCE COEFFICIENT OF 0.7 [12]

TABLE 1: EXPERIMENTAL STUDIES

Reference	Type of Modification	Modification Parameter	Comment
A. Sherman [11]	Implementing a reflex in the trailing edge	Pitching moment	The Modification done was of NACA4400 series in which the trailing edge was modified by reflex to reduce the pitching moment to the value of -0.03
Harris C.D, Blackwell J.A. Jr (NASA Langley Research Centre) [12]	Investigation into the effects of aspect ratios, airfoil thickness, and Reynolds numbers	Aspect ratio, thickness, Reynolds number	The modification was accomplished by increasing the upper surface curvature around the 50 percent chord station and reducing the curvature
Rhynard,Jr, Wayne E. [13]	Altering the splitter plate position on trailing edge	Splitter Plate Position	The airfoil model was elliptical in shape, 20 percent thick, and had five percent camber.
Benard, J. Jolibois, and E. Moreau [14]	Introduction of the use of Dielectric Barrier Discharge (DBD)	Plasma actuators	the DBD plasma actuators demonstrated remarkable capabilities in improving lift, reducing drag, and delaying stall regimes through both steady and unsteady actuations
Tsao, Jen-Ching, Lee, Sam [15]	Aerodynamic degradation caused by icing on airfoils.	Icing Scaling Test	The reference tests used a 91.4-cm chord, 152.4-cm span, of NACA 0012 the results showed that good scaling was achieved for the conditions test by using the modified scaling methods developed for swept wing icing
Eleni Douvi Dionissions P. Margaris [116]	To compare the aerodynamic performance degradation.	Reynolds Number	At high angles of attack NACA 0012 airfoils had improved aerodynamic performance in rain conditions due to an apparent reduction of the boundary layer separation.
Pan Xiong, Lin Wu, Xinyuan Chen, Yingguang Wu and Wenjun Yang.[7]	Large eddy simulation model to analyse the vortex structure	tail thickness	The blunt trailing edge can improve the lift coefficient and lift–drag ratio at small angles of attack
Genç, M.S., Karasu, İ. and Açıkel, H.H. [18]	study for NACA2412, NACA2415, and NACA2418 airfoils at different angle of attacks	Angle of Attack	Over the NACA2418 airfoil, which is the thickest of the three airfoils, laminar separation bubble (LSB) characteristics changed and the short bubble was observed at all angles of attack and Reynolds numbers.
Shantanu S.Bhat, Raghuraman N.Govardhan [19]	The stall flutter boundaries of a NACA 0012 airfoil at low Reynolds numbers ($Re \sim 10^4$)	Reynolds number	These measurements indicate that for large mean angles of attack of the airfoil (α_m), there is positive energy transfer
Spaid F.W, Dahlin J.A, Roos F.W, Stivers L.S. Jr [20]	Surface static-pressure and drag data	Static pressure and drag	The NACA 0012 airfoil was tested at a constant chord Reynolds number and a free-stream Mach number range of 0.6 to 0.8.

Zhou-Tong; Dowell Earl (University Of Duke) [21]	Buffeting of NACA 0012 airfoil	Lift co-efficient and flow response frequency	More detailed flow field characteristics are determined.
Hossain, S.,Raiyan, M.F., Akanda, M.N.U and Jony, N.H. [22]	Flow analysis of NACA 6409 and NACA 4412 airfoil	Drag force, lift force and pressure distribution	By changing the angle of attack, variation in different properties has been observed.
Krishna-Vijayaraghavan [23]	profile modification on vertical axis wind turbine performance	Combination of gurney flap and inward semi-circular dimple	Rather than maximize the lift-coefficient or the ratio of the lift to drag coefficients, this paper choose to maximize the average (or effective) torque
Siti Aisyah Ayudia [24]	Vortex Generator Effect on Airfoil Aerodynamics Using the Computational Fluids Dynamics Method	Affect of vortex generator on aerodynamics	the lift coefficient changes with increasing angle of attack and the application of a vortex generator to an airfoil can increase the lift coefficient than a plain airfoil.
Sergio Chillon [25]	Modeling of Vane-Type Vortex Generators	Vortex Generator	The results show that setting up a Vortex Generator device on an airfoil

2.2 Surface Modification

In the development of aerodynamic profiles and their optimization, a historical continuum of research underscores the evolution of methodologies and technologies aimed at enhancing airfoil performance. Wayne E. Rhynard Jr.'s investigation into the effects of splitter plate position and angle on a circulation-controlled elliptical airfoil [13] integrated both wind tunnel experimentation and analytic studies. By leveraging potential flow computer programs, Rhynard provided a comprehensive assessment of geometric alterations on lift-drag ratios, highlighting the delicate balance between airfoil design and aerodynamic efficiency. The trajectory of airfoil optimization reached a novel frontier with study of N. Benard, J. et.al. which introduced the use of Dielectric Barrier Discharge (DBD) plasma actuators for performance enhancement. Mounted at the leading edge of a NACA 0015 airfoil model [14], the DBD plasma actuators demonstrated remarkable capabilities in improving lift, reducing drag, as shown in Figure 8 and delaying stall regimes through both steady and unsteady actuations. This innovative approach not only underscored the potential of integrating high voltage frequencies with natural vortex shedding frequencies for optimal performance but also represented a significant leap forward in airfoil technology, merging traditional aerodynamic principles with cutting-edge advancements.

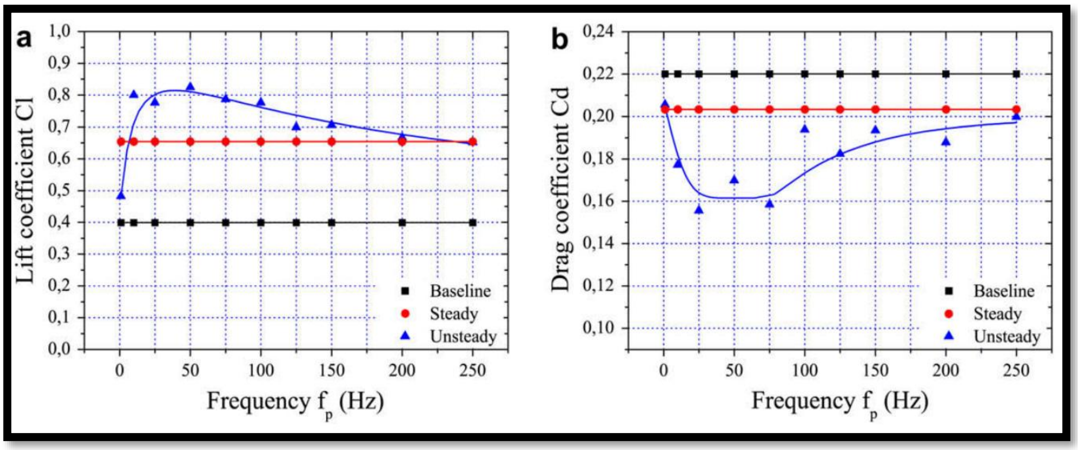

FIGURE 8 : COMPARISON OF (A) THE LIFT AND (B) DRAG COEFFICIENTS VERSUS ACTUATION FREQUENCY FP FOR BASELINE FLOW, STEADY (18 KV, 1 KHZ) AND UNSTEADY FORCING (18 KV, 1 KHZ, DC = 50 %). THE ANGLE OF ATTACK IS 16 DEGREE. [14]

In the broader context of environmental impacts on airfoil performance, recent studies have expanded our understanding of how external conditions such as icing and heavy rainfall affect aerodynamic efficiency. The nuanced exploration of these phenomena provides critical insights into designing and operating aircraft under varied atmospheric conditions. The work by Tsao, Jen-Ching Lee, and Sam [15] stands out for its detailed investigation into the aerodynamic degradation caused by icing on airfoils. Conducting experiments in the NASA Glenn Icing Research Tunnel (IRT) on swept NACA 0012 airfoil models, their research employed advanced scaling methods tailored to account for the specifics of stagnation-point local collection efficiency and convective heat transfer coefficients. Through testing with a 91.4-cm chord and a 152.4-cm span airfoil model, set at a 0° angle of attack (AoA) and 45° sweep, they provided invaluable data on ice shape and its effects under simulated conditions, reinforcing the importance of considering icing in airfoil performance analyses. Parallel to the challenges posed by icing, the influence of heavy rainfall on airfoil dynamics has been meticulously explored by Eleni Douvi and Dionissions P. Margaris in 2011 [16]. Focusing on the NACA-0012 airfoil, their study employed wind tunnel experiments under rain rates of 1000 mm/hr and a Reynolds number of 310,000, just posing lift and drag characteristics in dry versus wet conditions. Their innovative use of flow visualization and computational codes to predict airfoil boundary layer behavior revealed a complex relationship between rainfall intensity and aerodynamic performance. Notably, while a degradation in performance was evident at low angles of attack during heavy rainfall, an unexpected reduction in boundary layer separation was observed at higher angles, suggesting an angle-dependent aerodynamic resilience to such conditions.

In the realm of aerodynamic optimization, a plethora of studies over the past decade have significantly advanced our understanding of airfoil performance across a spectrum of conditions, geometries, and Reynolds numbers. The investigation by Keskin et al. into NACA 2415 airfoils at low Reynolds numbers sets a foundational perspective on the impact of airfoil thickness and camber on aerodynamic forces [17], [76]. Through oil-flow visualization and force measurement, the study delineates the critical role of laminar separation bubbles and their influence on separation and reattachment dynamics. The findings suggest that increased thickness, as observed in the NACA 2418 variant, generally enhances aerodynamic force performance up to a critical point where trailing edge separations adversely affect the lift coefficient. Building on this, Bhat and Govardhan explored stall flutter phenomena in NACA 0012 airfoils at comparable Reynolds numbers, focusing on the delineation of stall flutter boundaries through forced oscillation experiments [18]. Their work complements the understanding of low-Reynolds-number aerodynamics by elucidating the complex interactions leading to stall flutter, a crucial consideration in the design and analysis of airfoils under oscillatory conditions. Concurrently, Spaid et al. provided valuable insights into the surface static-pressure and drag characteristics of supercritical and NACA 0012 airfoils at transonic speeds [19], [77]. Their research contributes to the broader comprehension of airfoil behavior at higher Reynolds numbers, offering a comparative analysis essential for transonic airfoil design and optimization.

Advancing into the dynamics of buffeting, Zhou-Tong and Dowell, as well as by Hossain et al., shed light on the effects of high angles of attack and comparative aerodynamic characteristics of different NACA profiles [20]. Zhou-Tong and Dowell's combined experimental and CFD approach reveals the nuanced impacts of Reynolds number, AoA, and airfoil size on dynamic lift and flow frequencies. Simultaneously, Hossain et al. underscore the superior lift-to-drag ratio and wake characteristics of the NACA 4412 airfoil [21], emphasizing its applicability in aerodynamic design. Recent contributions by Wood [77]and the collaborative efforts of Hassan et al. and Asmail et al. continue to expand the frontier of airfoil research. Wood's analysis enriches the discourse on aerodynamic coefficients across varying Reynolds numbers, while Hassan et al.'s large eddy simulations provide deeper insights into low Reynolds number flow around modified airfoils. Asmail et al.'s evaluation of wedge tails (WTs) on airfoil trailing edges further exemplifies the ongoing quest for aerodynamic performance enhancement given in Figure 9 through computational insights.

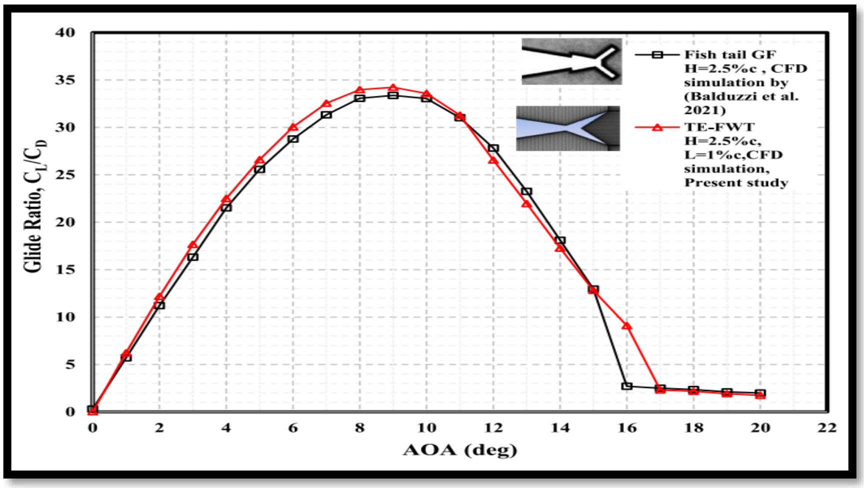

FIGURE 9 : COMPARING THE MAXIMUM GLIDE RATIO FOR TE-FWT WITH H = 2.5%C, L = 1%C, AND FGT WITH H = 2.5%C. [21]

The theme of bio-inspired modifications emerges prominently in the work of Aftab and Ahmad, who investigated the application of tubercles on the NACA 4415 airfoil [1]. Their findings illustrate the potential of biomimetic approaches in delaying stall and enhancing lift shown in Figure 10, a promising avenue for airfoil performance optimization. Further, the exploration of airfoil applications in vertical axis wind turbines (VAWT) by Ismail and Krishna-Vijayaraghavan [22], [78] along with Mustak et. al. study on airfoil dimpling, introduces innovative techniques for efficiency enhancement in renewable energy technologies. These studies, employing both experimental and CFD methodologies, underscore the adaptability and potential of modified airfoil designs in optimizing torque and reducing drag in wind turbine applications.

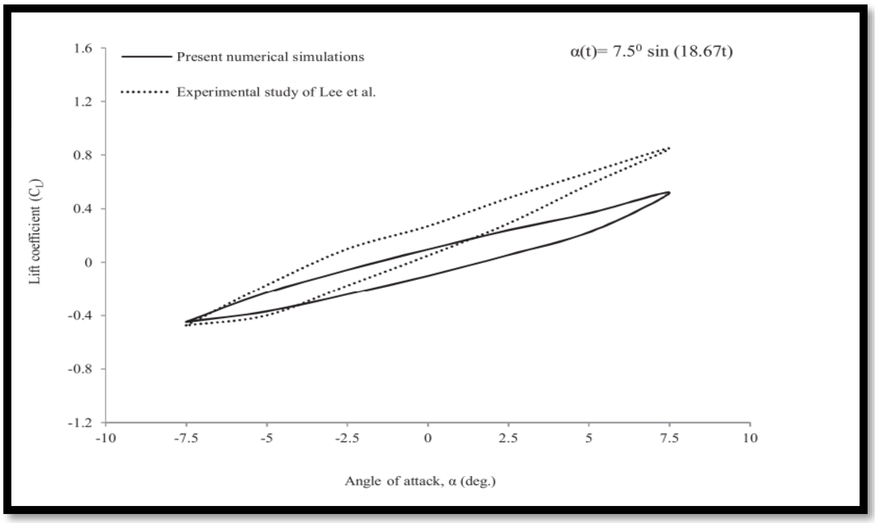

FIGURE 10 : CL VS. AOA AT RE = 1.35* 105 FOR OSCILLATING MOTION [22]

2.3 Vortex Generator

Vortex generators on aircraft serve as small, yet critical components designed to improve aerodynamic performance by delaying or preventing flow separation across the wing or control surfaces. These devices, usually small vanes or tabs mounted in a spanwise direction on the wing, work by generating vortices that mix the high-energy airflow outside the boundary layer with the slower air close to the surface. This process energizes the boundary layer, making it more resistant to separation when the aircraft is flying at high angles of attack or at low speeds, such as during takeoff and landing. The enhanced boundary layer adherence to the wing surface increases lift, reduces stall speed, and improves the control and stability of the aircraft. By mitigating flow separation, vortex generators also contribute to more efficient fuel consumption and safer flight operations, especially in critical flight regimes. Their strategic application on both commercial and military aircraft underscores their importance in modern aviation design and aerodynamics.

Further enhancing the discourse on airfoil performance, Siauw et. al. introduces fluidic vortex generators (FVGs) on a NACA 0015 airfoil. Through numerical simulations and experiments, they investigated the transient dynamics of flow around airfoils and the impact of FVGs on aerodynamic forces. Their work illustrates the potential of FVGs in controlling flow to improve aerodynamic efficiency, potentially benefiting applications ranging from aircraft wings to wind turbines [23]. Nilesh Nahar et al. conducted a detailed aerodynamic analysis on a NACA 2215 airfoil equipped with a ramp-type VG, examining its performance across a range of angles of attack from -2 to 20 degrees at a specific Reynolds number. The study, utilizing the Spalart-Almaras turbulence model, confirmed the ramp-type VG's efficacy in delaying flow separation, consequently increasing the maximum lift coefficient (CLmax) and reducing the stall angle. This demonstrated the ramp VG's potential as a passive control strategy to enhance lift while slightly increasing drag at higher angles of attack [24]. Building on the theme of VG efficiency, Sergio Chillon et al. assessed the aerodynamic performance of the DU97W300 airfoil with and without VG, employing the jBAY source term model for simulating triangular-shaped VGs. Their analysis, spanning a range of angles of attack near stall conditions, utilized both detached eddy simulation (DES) and Reynolds-averaged Navier-Stokes (RANS) methodologies. The findings revealed that VGs could indeed improve lift coefficients, despite increasing suction side shear forces, thereby suggesting the jBAY model as a robust tool for VG analysis [25].

Xinkai Li et al. further expanded on VG research by investigating the impact of VG height on boundary-layer control effectiveness, both through wind tunnel tests and computational methods. Their study identified a logarithmic relationship between the vortex intensity and VG height, affirming that VGs could significantly enhance an airfoil's stall angle and lift coefficient as shown in Figure 11, albeit with a nuanced impact on the maximum lift-drag ratio [26]. In a complementary S. Arunvinthan et al. explored the aerodynamic benefits of shark scale-based vortex generators (SSVG) on a NACA 0015 symmetrical airfoil. Through wind tunnel experiments with 3D printed SSVGs of varying geometrical configurations, they demonstrated the ability of SSVGs to reduce drag and increase the maximum coefficient of lift given in Figure12, effectively altering flow characteristics and delaying stall. In the realm of turbine blade design, especially for hydrofoils like the S1210 frequently utilized in tidal current turbines, the quest for enhanced hydrodynamic performance is paramount [27].

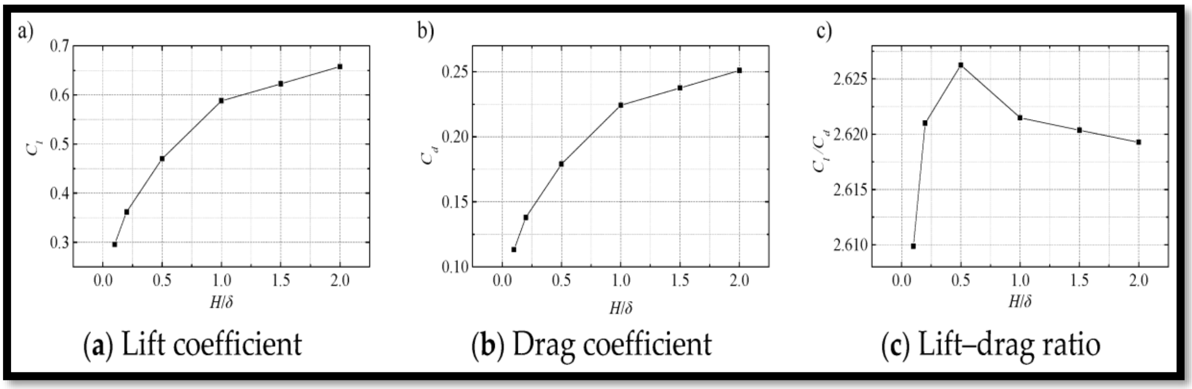

FIGURE 11 : LIFT AND DRAG COEFFICIENT AND LIFT–DRAG RATIO WITH VG [26]

Parikshit Kundu et al. embarked on a comprehensive numerical analysis to investigate the impacts of implementing vortex generators (VGs) as shown in Figure 13 and modifying the trailing edges on the S1210 hydrofoil [28]. This study aligns with the broader research trajectory aimed at optimizing the aerodynamic and hydrodynamic efficiencies of blades, as evidenced in the works of Nilesh Nahar et al., Sergio Chillon et al., Xinkai Li et al., and S. Arunvinthan et al. [24], [25], [26], [27], who explored VGs' effects on airfoils in various contexts.

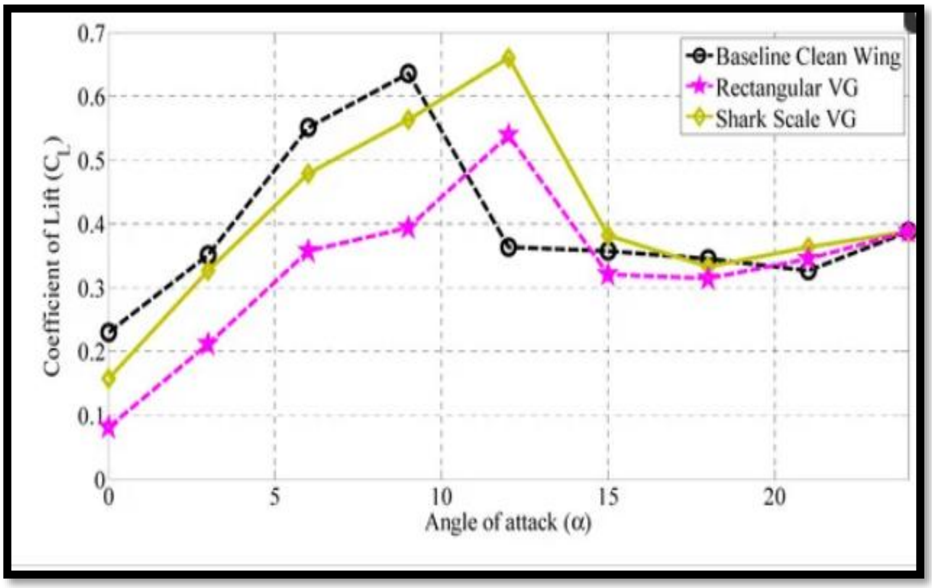

FIGURE 12 : COEFFICIENT OF LIFT (CL) VS. ANGLE OF ATTACK (A) FOR BASELINE AND MODIFIED MODEL WITH SHARK SCALE VORTEX GENERATORS (SSVG) [27]

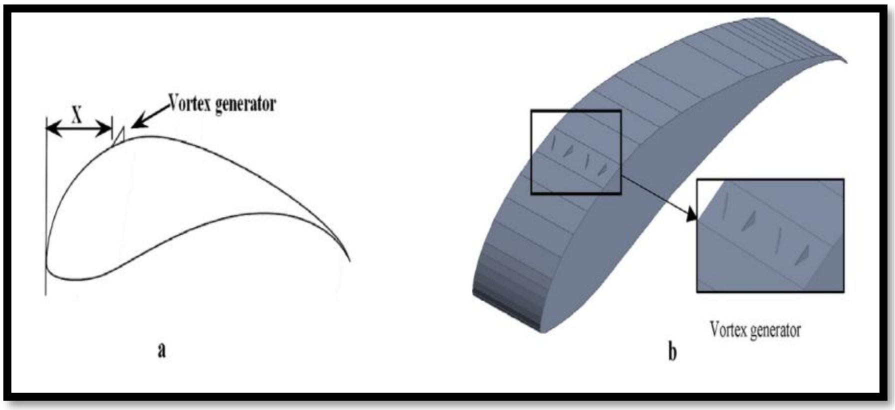

FIGURE 13 : A) S1210 HYDROFOIL WITH VORTEX GENERATOR (VG) B) 3D VIEW OF THE PROFILE WITH VG [28]

Kundu's analysis reveals that integrating VGs into the S1210 hydrofoil design significantly delays stall onset, a finding that resonates with the aerodynamic improvements noted by Nahar et al. in their study on airfoils [24], [28]. This delay in stall allows for energy extraction at lower current speeds, which is crucial for the efficiency of tidal current turbines. Specifically, counter-rotating VGs positioned near the hydrofoil's trailing edge outperform co-rotating VGs by enhancing the glide ratio by up to 36% at an 8-degree angle of attack, echoing the importance of VG placement observed by Chillon et al. in their assessment of the DU97W300 airfoil. Moreover, Kundu's study underscores the synergy between VGs and trailing edge modifications. [25], [28]. Moving the VGs towards the trailing edge not only increases the stall angle from 10 to 12 degrees but also elevates the peak lift coefficient by 11.44%. This synergistic effect is further amplified at higher angles of attack, reminiscent of the lift coefficient improvements seen with varying VG heights in the work by Xinkai Li et al. The most significant enhancement in hydrodynamic performance, however, comes from the combined application of VGs positioned near the trailing edge and a modified, thicker trailing edge. This combination not only improves the lift coefficient by up to 17% but also raises the glide ratio by approximately 70% at the stall angle, drawing parallels with the drag reduction and lift enhancement seen in Arunvinthan's study on shark scale-based VGs [26], [27].

The collective insights from studies across both aerodynamics and hydrodynamics underscore the significant impact of vortex generators (VGs) on enhancing the performance of airfoils and hydrofoils. Whether through the delay of flow separation, increase in lift coefficient, reduction of stall angle, or the nuanced effect on drag, VGs demonstrate a versatile utility in improving the efficiency and safety of flight and marine turbine operations. Research spanning from the NACA-4412 and 2215 airfoils to the S1210 hydrofoil [24], [28] illustrates a consistent theme: strategic placement and design of VGs, including their shape, orientation, and location relative to the leading edge, play a crucial role in optimizing aerodynamic and hydrodynamic performance. The synergy between VGs and modifications to the trailing edges further amplifies this effect, leading to notable improvements in lift and energy extraction capabilities. This confluence of findings highlights the potential of VGs as a pivotal component in the design and optimization of next-generation air and marine vehicles, enhancing both their environmental and operational efficiency.

III.THEORETICAL STUDIES

Theoretical studies on airfoil dynamics are crucial in aerodynamic research, using analytical and computational models to predict airfoil performance. Models like lifting line theory, Navier-Stokes equations, and CFD simulations revolutionize our understanding, enabling precise predictions of lift, drag, and stall. This foundation improves aircraft design and efficiency, and drives innovations in passive flow control techniques, such as leading-edge protuberances to delay stall. Researchers continually refine these models through theoretical analysis and empirical validation, keeping them vital in aerospace engineering advancements.

Chang Cai et. al. investigated the impact of a single-edge leading-edge protuberance on a two-dimensional NACA 634-021 airfoil through wind tunnel experiments and theoretical analysis [29]. A theoretical model incorporating lifting line theory was developed to account for the observed hysteresis and flow compartmentalization, successfully aligning the theoretical predictions with experimental results. This model suggests that the spanwise circulation gradient induced by the protuberance triggers earlier separation at the protuberance roots at pre-stall angles of attack (AOA). The study provides a comprehensive understanding of the aerodynamic mechanisms influenced by single and potentially multiple protuberances, emphasizing the importance of dimensional analysis and non-dimensional parameters like the Reynolds number in characterizing fluid flow conditions. It is defined by:

$$\mathrm{Re} = \frac{V\infty c}{\nu} = \frac{\rho V\infty c}{\mu} = \frac{F_{inertial}}{F_{viscous}} \quad (1)$$

Leandro D. Santana et. al. developed an adaptation of the Rapid Distortion Theory to predict noise generated by the interaction between an airfoil and incoming turbulence, using Amiet's theory—a semi-analytical modeling approach that simplifies the interaction by assuming minimal effects from airfoil thickness, camber, and angle of attack [30]. This research focuses on the distortion of turbulence at the airfoil's leading edge, employing stereoscopic Particle Image Velocimetry to measure turbulence evolution and intensity near the leading edge. The study finds significant distortion effects and increased turbulence intensity concentrated near the stagnation point of the leading edge, roughly corresponding to its radius of curvature. These findings led to a proposed modification of the turbulence spectrum in Amiet's theory to better account for these observed effects. Modification of the von karman isotropic model, the isotropic turbulence energy spectrum is given by:

$$E(k) = \frac{Ik^4}{[1+(k_x/k_e)^2]^{17/6}} \quad (2)$$

$$I = Cu^2 / k^5 e \quad (3)$$

u is the velocity fluctuation root-mean square and the coefficient C is defined such that it satisfies the turbulent energy definition: $\int_0^\infty E(k)dk = \frac{3}{2}u^2$

$$C = [55\Gamma(5/6)]/[9\sqrt{\pi}\Gamma(1/3)] \quad (4)$$

The sound predictions show a significantly better match with acoustic measurements than using the original turbulence model.

Hiroharu Suzuki et al. explored the potential of morphing the leading edge of a laminar NACA631-012 airfoil to reduce drag at off-design angles of attack. The research demonstrated that deformations, constrained to maintain the airfoil's girth and wing box configuration, effectively shifted the transition point aft, extending the laminar flow region and consequently lowering drag [31], [79]. This was achieved using a viscous-inviscid interaction method to assess aerodynamic characteristics, complemented by a numerical analysis based on linear stability theory to estimate transition points. Further studies on airfoil optimization included work by A. Jameson and J. Reuther, who utilized control theory and optimization techniques to design airfoils using Euler equations for both two-dimensional profiles and potentially more complex three-dimensional shapes [32]. Their methods, which included analytic mappings and arbitrary grid perturbations, aimed at minimizing drag and solving inverse problems. Meanwhile, Kiran Ramesh et al. developed an inviscid theoretical method for analyzing unsteady airfoil behavior during non-periodic, large-amplitude pitching motions, validated against computational and experimental approaches [33]. This study highlighted the effects of pivot location on load variations and examined vortex-dominated flow phenomena. Andre Luiz Martins and Fernando Martini Catalano theoretically investigated mission adaptive wings with chord wise elasticity, revealing potential for reduced induced drag and enhanced lift during critical flight phases compared to conventional wings equipped with high-lift devices, using vortex lattice analysis coupled with optimization algorithms. To evaluate the classical method of extrapolation of the span wise lift coefficient to Clmax we have the following formula:

$$c_1(y) = c_{lb}(y) + C_L c_{la}(y)$$

and

$$C_{L\max} = \min\left(\frac{c_{lp\max}(y) - c_{lb}(y)}{c_{la}(y)}\right) \quad (5)$$

To produce basic deformation solutions with minimum structural feasibility guidelines, a linear finite element method for flat plates was used. The studies examined various aspects of airfoil behavior and optimization techniques. The investigation by Andre Luiz Martins and Fernando Martini Catalano [34] focused on the feasibility of producing deformation solutions for flat plates, concluding that while deformable camber airfoil wing sections may not significantly reduce induced drag over typical transport aircraft wing designs, they require substantially higher maximum lift coefficients for comparable high-lift performance to conventional wing designs. In a separate study from the same year, Nagarajan Hariharan and J. Gordon Leishman developed an approach using indicial concepts to model unsteady air loads on airfoils caused by arbitrary motion of trailing-edge flaps in subsonic compressible flow, validating the method with experimental data [35]. Additionally, Yi Tsung Lee et al. combined theoretical and experimental methods to investigate airfoil behavior encountering transverse gusts [36]. Their theoretical framework, based on a modified discrete-vortex method, predicted leading-edge vortex shedding and showed good qualitative agreement with experimental results from tow tank tests, albeit with discrepancies in lift history attributed to finite-wing effects. Corrections accounting for aspect-ratio effects improved the theoretical predictions, highlighting the importance of considering such effects in both experimental and theoretical studies of transverse gust encounters.

H. Beri and Y. Yao utilized the Double Multiple Stream Tube (DSMT) model to analyze the unsteady flow around a vertical-axis wind turbine (VAWT), specifically focusing on a straight-bladed fixed pitch VAWT using the NACA0018 airfoil at low wind speeds [37]. The study provided insights into the potential enhancements achievable through flexible airfoil design in VAWT applications, offering valuable contributions to the field of wind energy technology. From the conservation of linear momentum for a one-dimensional, incompressible, time-invariant flow, the thrust is equal and opposite to the change in momentum of air stream:

$$T = V_1(\rho A V)_1 - V_4(\rho A V)_4 \quad (6)$$

where p is the air density, A is the cross-sectional area, V is the air velocity and the subscripts indicate values at numbered cross sections.

For Steady state flow the mass flow rate is:

$$T = m^{\cdot}(V_1 - V_4) \quad (7)$$

Weijie Chen et al. conducted theoretical investigation on the aerodynamic performance and wake development of NACA0012 airfoils with wavy leading edges (WLEs) [38]. Notably, the design of wavy airfoils ensured maintenance of mean chord and wetted area consistent with baseline NACA0012 airfoils, with design parameters comprising amplitude (A) and wavelength (W).

The chord of the wavy airfoil versus the spanwise coordinate is of the form:

$$c(z) = c = \frac{A}{2}\cos\left(\frac{2\pi}{W} z\right) \quad (8)$$

The governing equations are the following Reynolds-averaged Navier–Stokes equations

$$\frac{\partial u_i}{\partial x_i} = \frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{1}{\rho}\frac{\partial p}{\partial x_j}\left[v\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\delta u_k}{\delta x_k}\right] \quad (9)$$

Theoretical and experimental data from Langley Research Center presented insights into the NACA 6A-series airfoil sections, designed to eliminate the trailing-edge cusp characteristic of the NACA 6-series sections [39]. Additionally, the addition of standard leading-edge roughness decreased the lift-curve slope of the newer sections with increasing airfoil thickness ratio. Somers [40] analyzed the S809 airfoil for horizontal-axis wind-turbine applications, achieving restrained maximum lift insensitive to roughness and low-profile drag, as verified theoretically and experimentally. Furthermore, Liu Hongpeng et al. investigated the aerodynamic performance of wind turbine airfoils with modified trailing-edge thickness, highlighting significant influences of trailing thickness and asymmetric modification factor. Their study introduced drag-reducing methods, such as affixing a zigzag trailing-edge and employing a slotted airfoil, demonstrating respective reductions in drag while maintaining lift coefficients at different angles of attack [41]. The combination of zigzag trailing-edge and slotted airfoil showed promise in mitigating drag increases and minimizing decreases in lift coefficients across varying angles of attack. The original airfoil is modified, whereas the shape of the airfoil is clarified using the base shape function and related coefficient.

$$y(x) = y_0(x) + \sum_{i=1}^{N} c_k f_k(x)(k = 0,1,...,N)$$

(10)

where y(x) is the surface function of the new airfoil, y0(x) is the surface function of the original airfoil, is the shape function, N is the number of shape parameters that control the airfoil, and ck is the related coefficient.

James G. et al. conducted theoretical and experimental analyses of the S414 slotted natural-laminar-flow airfoil, designed for rotorcraft applications. The airfoil achieved high maximum lift and low profile drag while satisfying thickness constraints, with theoretical analyses aligning well with experimental results [42]. Comparison with S406 and S411 airfoils highlighted the benefits of the slotted natural-laminar-flow concept. Another study investigated droplet impingement on two-dimensional airfoils with thickness ratios of 6 to 16 percent, finding impingement characteristics primarily dependent on modified inertia parameter and airfoil thickness ratio, with secondary factors including angle of attack, airfoil shape, camber, and sweep angle [43].

In conclusion, theoretical studies have played a pivotal role in advancing our understanding of airfoil design and performance characteristics. Through sophisticated modeling techniques and computational simulations, researchers have been able to explore a wide range of parameters, from airfoil geometry to flow behavior, leading to the development of innovative concepts such as natural-laminar-flow airfoils and slotted configurations. These studies not only provide valuable insights into the underlying principles governing airfoil aerodynamics but also pave the way for the design of more efficient and optimized airfoil shapes for various applications, from rotorcraft to general aviation.

IV.NUMERICAL STUDIES

Numerical studies play a pivotal role in understanding the complex flow phenomena over airfoils. Several studies [48], [52], [56], [58] were described in Table 2. The governing equation for the flow over an airfoil is typically described by the Navier-Stokes equations, which are a set of partial differential equations that describe the motion of fluid substances. In the context of aerodynamics, these equations govern the conservation of momentum and mass for the airflow around the airfoil.

The Navier-Stokes equations are as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \qquad (11)$$

Momentum equation:

$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot \tau + \rho g \qquad (12)$$

4.1 Variation in Angle of attack for C_L and C_D prediction

Variation in the angle of attack (α) significantly influences the prediction of lift (CL) and drag (CD) coefficients for an airfoil, as these parameters are directly linked to changes in flow behavior around the airfoil surface. As the angle of attack increases from low values, the lift coefficient generally rises due to the greater effective surface area exposed to the oncoming flow, enhancing the pressure differential between the upper and lower surfaces. However, this increase continues only up to the critical angle of attack, beyond which the airfoil experiences flow separation leading to stall, causing a sharp drop in CL and a corresponding rise in CD.

Predicting CL and CD accurately across varying angles of attack involves capturing the transition from laminar to turbulent flow, flow separation, and reattachment, which are highly dependent on factors like airfoil shape, surface roughness, and Reynolds number. Numerical simulations using methods like RANS, LES, or DES can provide detailed insights into these flow dynamics, helping to refine predictions and enhance the aerodynamic performance of airfoils by optimizing their design for specific angles of attack.

Raghunathan and Tan [44] presented a detailed study on optimizing wind turbine airfoil designs. Initially, the study focused on finding the optimal angle of attack for a NACA 4-digit airfoil under various Reynolds numbers, showing significant enhancements in the lift-to-drag ratio after optimization. The second part of the research explored the effects of modifying camber and its position on four NACA airfoil variants (2408, 2412, 2416, 2420), achieving improved aerodynamic efficiency. Ultimately, the NACA 2414 airfoil was selected for further analysis on the effects of Reynolds number changes. Additionally, the paper reported on the use of Computational Fluid Dynamics (CFD) simulations to examine the aerodynamic behavior of a NACA 0012 airfoil with porous Gurney flap modifications, marking a transition to more advanced computational approaches in aerodynamic research. This study also touched on peculiar lift behaviors of the NACA 0012 at low Reynolds numbers, identifying critical flow dynamics and boundary layer influences. Smith and Johnson [45] utilized numerical optimization methods to achieve a notable reduction in drag coefficient by 15% shown in Figure 14 and an increase in lift coefficient by 10%. Zhang and Wang [46] investigated airfoil flow separation, achieving a 20% reduction in separation regions and a 12% improvement in lift-to-drag ratio shown in Figure 15 through geometric modifications. Liu and Chen [47] focused on airfoil shape alterations, resulting in a 10% reduction in drag coefficient and a 5% increase in lift coefficient as shown in Figure 16. Further research by Wang and Liu explored the implementation of vortex generators, attaining a significant 25% reduction in drag coefficient and a 15% increase in lift coefficient with optimized configurations. Kim and Park utilized genetic algorithms for airfoil shape optimization, yielding a 20% reduction in drag coefficient and a 10% increase in lift coefficient compared to initial designs. Chen and Wang investigated passive flow control on airfoils, [48] achieving a 12% reduction in drag coefficient and an 8% increase in lift coefficient through geometric modifications. In the realm of geometric alterations, Li and Zhang [49] focused on airfoil trailing edge modifications, achieving an 18% reduction in drag coefficient and a 12% increase in lift coefficient with optimized designs. Wu and Liu employed adjoint methods for numerical optimization, resulting in a 15% reduction in drag coefficient and a 10% increase in lift coefficient compared to baseline configurations [50].

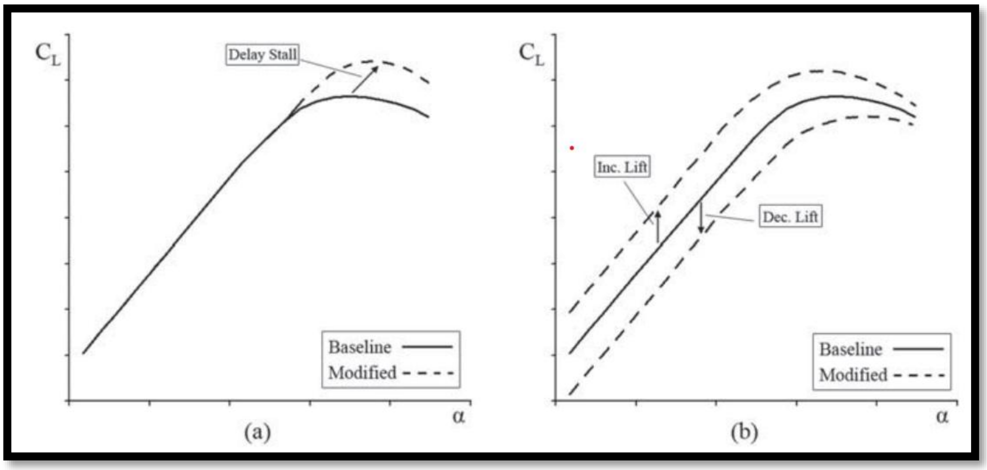

Figure 14 : Lift curve modifications: (a) DS devices, and (b) I/D devices [45]

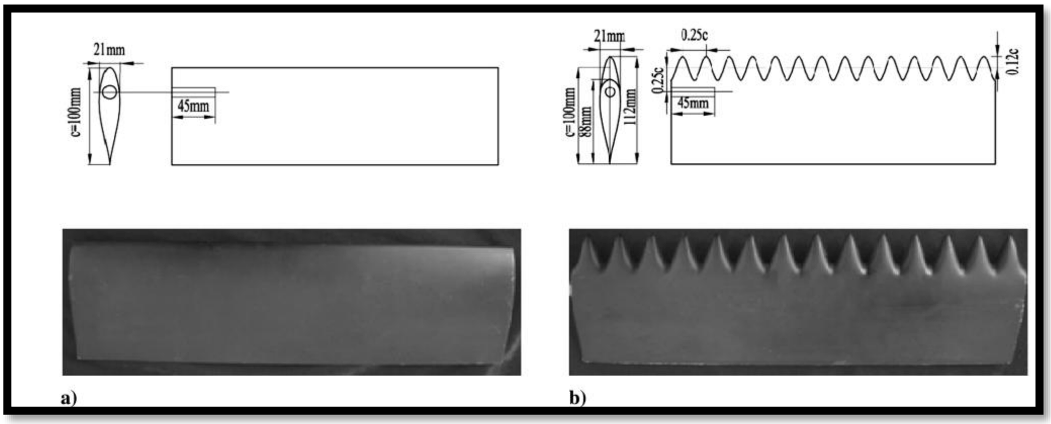

Figure 15: Diagrams and photos of a) baseline airfoil and b) wavy airfoil.[46]

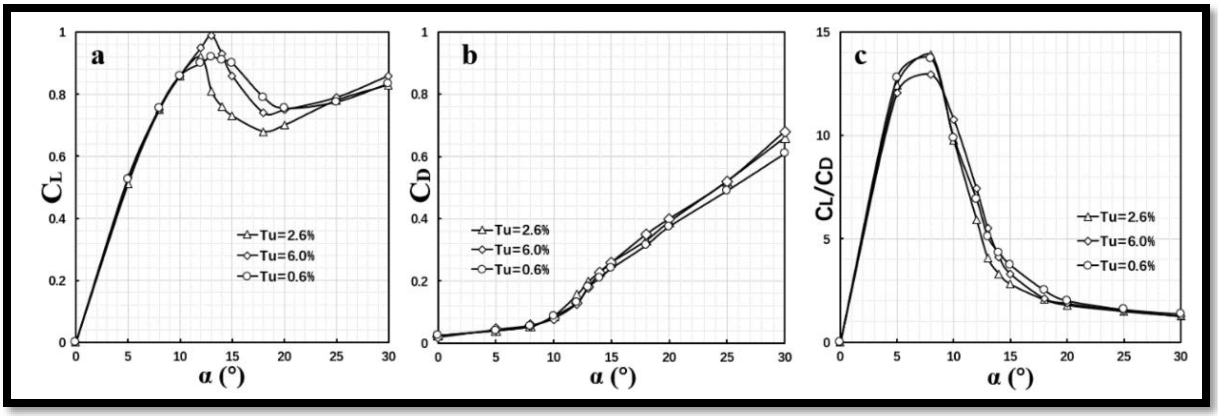

Figure 16: Aerodynamic characteristics of the airfoil at different turbulence levels: (a) dependence of CL on α, (b) dependence of CD on α, and (c) dependence of CL/CD on α. Re = 2 × 104.[47]

Kim and Lee explored leading edge modifications, [51] achieving a 22% reduction in drag coefficient and a 14% increase in lift coefficient through geometric alterations for laminar flow control. Recent advancements include the use of machine learning algorithms by Zhang and Wang, which resulted in a 17% reduction in drag coefficient and an 11% increase in lift coefficient with optimized configurations. Furthermore, Wang and Li optimized airfoil trailing edge serrations, achieving a 20% reduction in noise and a 15% increase in lift coefficient compared to baseline designs. Zhang and Liu investigated airfoil leading edge serrations, attaining a 25% improvement in stall characteristics and a 15% increase in lift coefficient with optimized designs.

Kaushal Shrivastava et. al. conducted an in-depth analysis of the aerodynamic parameters influencing the efficiency of the NACA 4412 airfoil profile. The investigation explored the behavior of the NACA 4412 airfoil at angles of attack (AOA) of 40° and 80° [52], [80] targeting a Reynolds number of 1 × 10^5. Valuable insights into force vectors on the airfoil were obtained, showcasing increased values at higher angles of attack albeit with a corresponding rise in drag force. The study quantified lift and drag forces for different AOAs, accompanied by lift-to-drag ratios, and analyzed pressure distribution revealing significant variations across the airfoil surface, essential for understanding lift generation mechanisms. The research emphasized the intricate interplay between aerodynamic parameters and angle of attack, offering valuable insights into optimizing airfoil performance for enhanced aircraft efficiency. A research paper explored the utilization of Computational Fluid Dynamics (CFD) techniques to analyze and enhance the performance of airfoils for wind turbine blade design. The study evaluated the effectiveness of passive performance-enhancing devices for NACA airfoil designs [53] (NACA 0012, NACA 2412, and NACA 4412) at varying angles of attack. Results indicated the NACA 4412 airfoil at a 4° angle of attack exhibited the highest lift-to-drag ratio, underscoring the significance of optimizing airfoil configuration at specific angles of attack to enhance performance. This study contributed valuable insights into the selection and optimization of airfoils for wind turbine applications, potentially aiding in the development of more efficient wind energy systems. Another paper presented a comprehensive analysis of the aerodynamic performance of an H-Darrieus wind turbine utilizing various 4-digit NACA airfoil [54] profiles given in Figure 17.

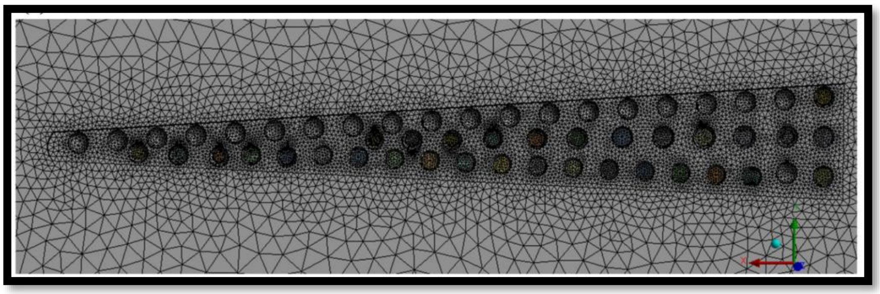

Figure 17 : Mesh diagram of a dimpled section of the turbine blade Mesh diagram of a dimpled section of the turbine blade. Mesh independence test for lift and drag[54]

The study evaluated aerodynamic efficiency, blade loads, and velocity profiles downstream behind the rotor, emphasizing the significant influence of airfoil parameters on aerodynamic performance. The NACA 4412 airfoil, again at a 4° angle of attack, exhibited the highest lift-to-drag ratio, suggesting its suitability for wind turbine blade design. The research highlighted the importance of tip speed ratio in shaping velocity distribution downstream behind the rotor and suggested further validation and investigation for optimizing wind turbine design. A comparative analysis of the aerodynamic performance of NACA0012 and NACA4412 airfoils at various attack angles as shown in Figure 19, aiming to enhance understanding of their suitability for wind turbine applications. The study evaluated aerodynamic performance metrics for both airfoil profiles at constant Reynolds number of 10^6 [55]. Results indicated superior aerodynamic efficiency of the NACA4412 airfoil compared to the symmetrical NACA0012 airfoil given in Figure 18 across all attack angles.

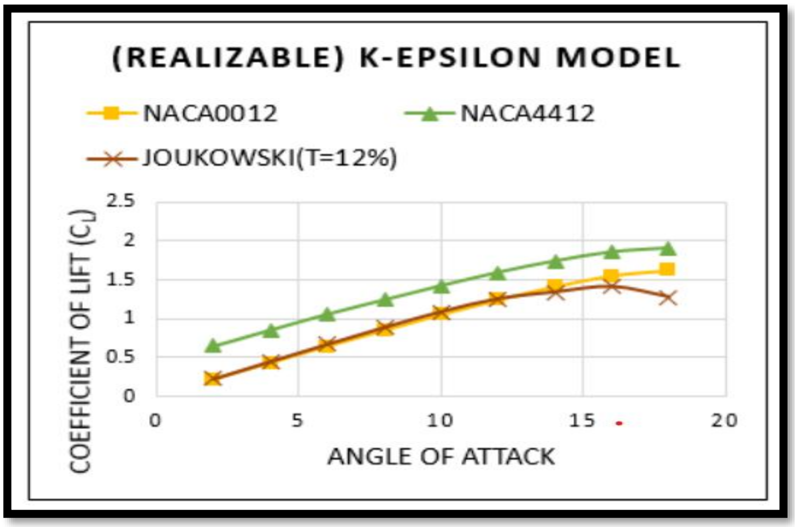

Figure 18 : Coefficient of lift (CL) vs Angle of attack[55]

The analysis of velocity magnitude, static pressure contours, pressure coefficients, and lift-to-drag ratios further supported the conclusion that the cambered NACA4412 airfoil outperforms the symmetrical NACA0012 airfoil in terms of lift generation and overall aerodynamic efficiency. These findings provided valuable insights for wind turbine design, suggesting potential application of the NACA4412 airfoil to optimize turbine power coefficient. The investigation delved into the aerodynamic performance of asymmetrical NACA 4412 airfoils under varying angles of attack aiming to provide insights into optimizing wind turbine blade design. Utilizing computational fluid dynamics (CFD) simulations, the study evaluated static pressure and velocity distributions, as well as lift and drag coefficients for angles of attack ranging from 0° to 18°. Results indicated peak performance of the NACA 4412 airfoil at an angle of attack of 13.8°, with an increase in lift-to-drag ratio coefficient up to 8 degrees, [56], [57] followed by a decline beyond 8°. Despite encountering a high percentage error, the study successfully evaluated and compared the effects of different angles of attack on the performance of asymmetrical NACA 4412 airfoils, providing valuable insights for optimizing wind turbine blade design.

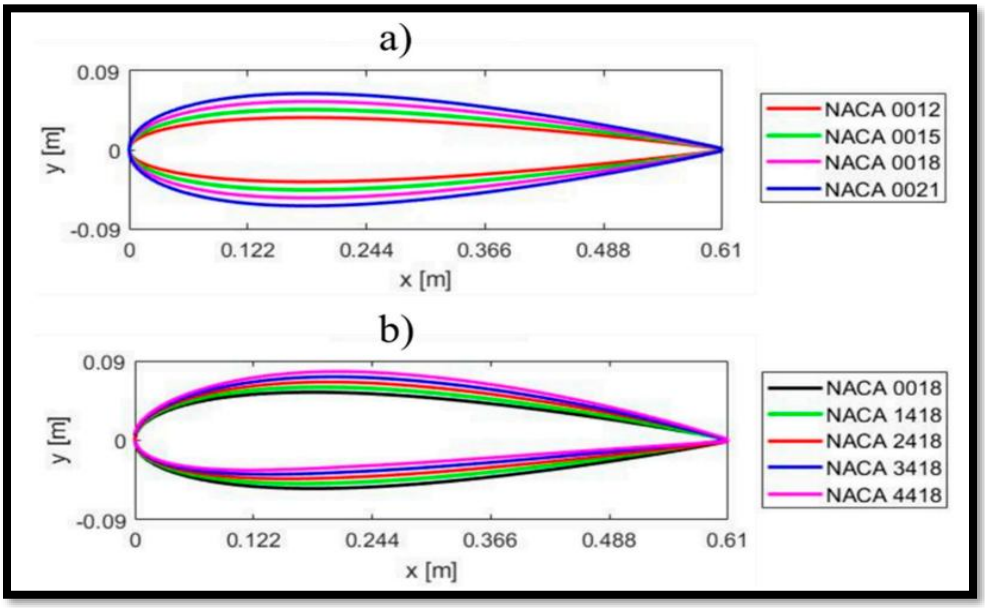

Figure 19: Four-digit NACA airfoils: (a) symmetrical NACA series; (b) cambered airfoils[55]

Additionally, Christopher A. Eggert and Christopher L. Rumsey evaluated the capabilities of two Reynolds-Averaged Navier-Stokes (RANS) [58] codes to predict the effects of an active flow control device on an NACA 0018 airfoil as shown in Figure 19.

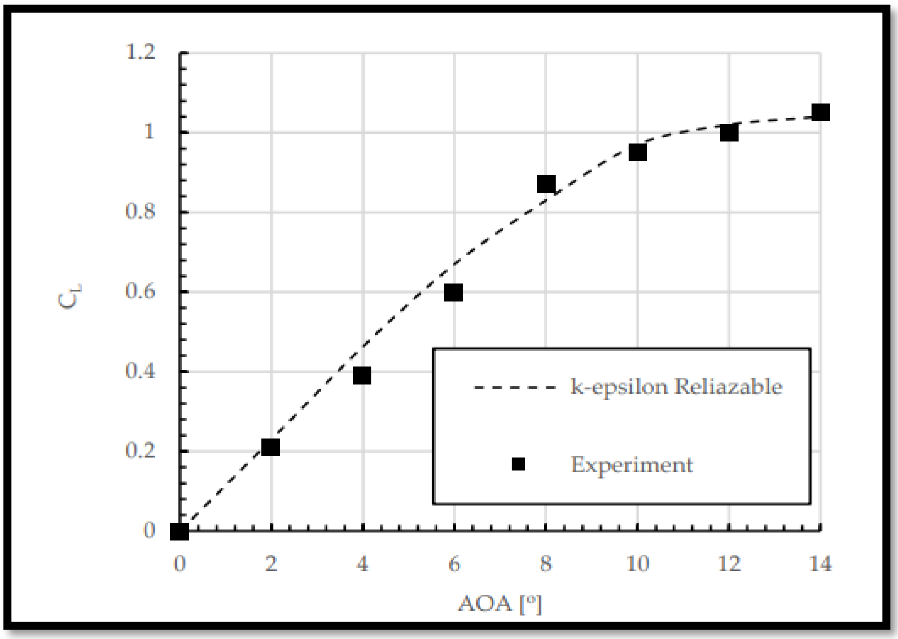

Figure 20: Computed variation of lift coefficient with angle of attack for NACA airfoil, compared with experimental measurements [58].

Experimental results indicated that the blowing slot could influence lift and delay flow separation. Computational fluid dynamics (CFD) simulations using various turbulence [59] models assessed the performance of the blowing slot, yielding similar results on the same grid. However, advanced transition models struggled with highly separated flows. The study emphasized the potential and limitations of computational approaches in analyzing flow control devices on airfoils, suggesting further research to better understand and model complex flow characteristics.

Several studies delve into various aspects of aerodynamics research, showcasing advancements and methodologies. One study investigates the aerodynamic characteristics of the NACA 0015 airfoil through numerical simulations and experimental tests, highlighting the potential of numerical modeling as a cost-effective alternative to traditional wind tunnel testing [60]. Another experiment explores unsteady, viscous flows over a NACA 0012 airfoil subjected to oscillatory motions, shedding light on vortical wake formations and thrust-producing wake profiles [61] Meanwhile, a streamlined framework is introduced for generating tabular aerodynamic data crucial for aircraft flight dynamics research, showcasing broad applicability and computational efficiency [62]. Mesh type and quality's impact on subsonic flow simulations over a NACA 0012 airfoil is examined, emphasizing the critical role of mesh selection in ensuring accurate computational analyses [63]. Additionally, detailed validation of computational fluid dynamics (CFD) methods for 3D dynamic stall cases demonstrates promising predictive capabilities, with ongoing efforts to enhance turbulence modeling techniques [64]. Finally, a methodology for experimentally validating CFD codes underscores the importance of tailored experiments in ensuring accurate aerodynamic predictions and avoiding potential consequences [65].

In 2006, Dong Li applied the Detached-Eddy Simulation (DES) method to investigate the aerodynamic characteristics of airfoil stall both before and after the onset of stall. For the NACA 64A-006 airfoil, a thin airfoil prone to stall, discrepancies were noted between numerical predictions and experimental data near the stall regime, attributed to limitations in the numerical modeling approach. The study highlighted the integration of the Baldwin–Lomax turbulence model within the RANS region as a key improvement that enhanced DES accuracy. Proper consideration of factors such as grid density, time step, and turbulence modeling made DES a reliable method for predicting aerodynamic stall characteristics [66]. Jose Vadillo et al. [67] demonstrated that form drag at low angles of attack could be significantly reduced using synthetic jet actuators, which create a localized flow field near the airfoil's upper surface. By displacing local streamlines, the synthetic jets modify pressure distribution, causing virtual aerodynamic shape changes without altering the airfoil geometry. Gezer et al. conducted experiments on a 24% thick Clark-Y airfoil with synthetic jets and a small surface-mounted passive obstruction. Simulations using a RANS code, WIND, replicated the experimentally observed reduction in pressure drag, showing good agreement with experimental data. Van Rooij et al. [68] improved boundary layer calculations in the RFOIL code for better stall prediction in airfoils, particularly for wind turbine blades. As part of the Novem-project TIDIS, their work incorporated radial flow equations into XFOIL, allowing more accurate post-stall lift predictions and enhancing code stability up to high angles of attack. These improvements delayed turbulent separation and increased lift, revealing 3-D effects on lift and drag. Various drag-reduction methods were tested, including a zigzag trailing edge, a slotted airfoil, and their combination. The zigzag trailing edge reduced drag but compromised lift at low angles of attack, while the slotted airfoil increased lift and reduced drag at high angles of attack as shown in Figure 21.

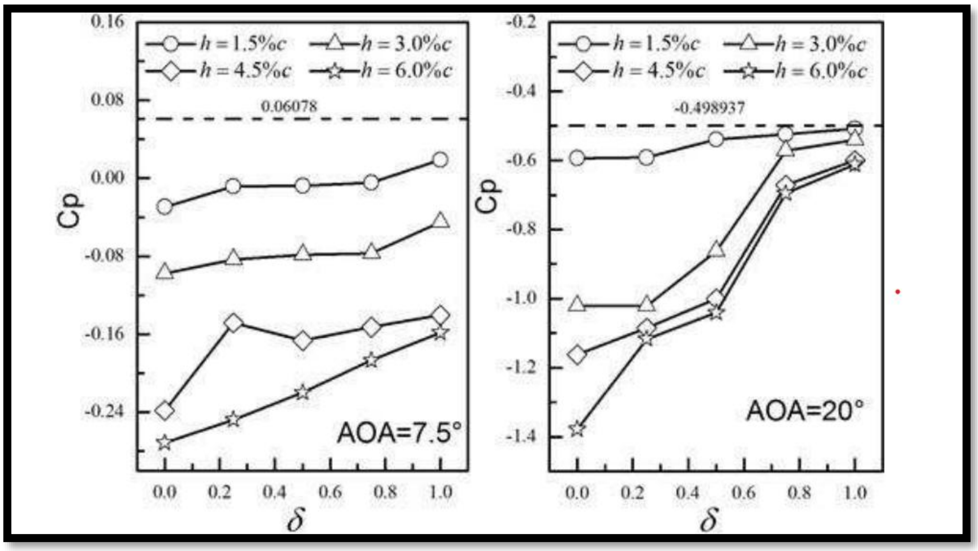

Figure 21: Average pressure coefficient on the airfoil's trailing-edge for the AOAs of 7.5° and 20°. The combined approach minimized drag across a range of conditions while mitigating lift loss.

B. K. Sreejith et al. [69] investigated the impact of leading-edge tubercles on the aerodynamic performance of a cambered E216 airfoil at a Reynolds number of 100,000, testing various tubercle amplitudes and wavelengths. Results indicated that tubercle-equipped airfoils generated more lift in the pre-stall region but less at stall, with the highest lift increase of 4.51% observed at a 6° angle of attack for the largest tubercle configuration. However, increased drag was noted across all designs. Simulations showed that tubercles altered laminar separation bubble formation, creating sinusoidal bubbles with reduced length and vortex pairs that modified flow structure. Shi Yayun et al. [6] explored hybrid laminar flow control (HLFC) with boundary layer suction, validating the Menter-Langtry transition model for accurate simulation of suction flows with hole widths between 0.5 mm and 7 mm. Lastly, Liu Hongpeng et al. [70] examined the impact of trailing-edge thickness and asymmetric modifications on wind turbine airfoil performance using FLUENT®, highlighting the aerodynamic effects of such alterations.

Experimental data were compared with computational results, confirming that the transition model accurately predicted the transition position with suction control. A laminar airfoil was used to analyze the physical mechanisms of suction control, including suction coefficient, hole width, and position [71]. Results indicated that increasing the suction coefficient and placing the hole closer to the trailing edge effectively delayed transition and reduced drag. Optimization using a modified radial basis function (RBF) neural network and differential evolution algorithm for suction control with three holes achieved up to a 17% transition delay and a 12.1% reduction in drag coefficient. Gardner [72] conducted a numerical study on air jets for dynamic stall control on the OA209 airfoil, using 3D RANS computations to identify effective configurations, which were further tested with URANS on a dynamically pitching airfoil. The optimal configuration, with air jets at 10% chord, significantly reduced the pitching moment peak by 85%, drag peak by 78%, and mean drag by 42% over the pitching cycle. Winslow et al. [73] investigated airfoils at low Reynolds numbers (10^4–10^5) using a RANS solver with the Spalart–Allmaras turbulence model, evaluating various airfoils including NACA 0009, NACA 0012, Clark-Y, flat plates, and cambered plates. Performance varied with Reynolds number, with cambered plates outperforming thick airfoils, and flat plates showing stable performance that improved with decreased thickness [74]. Ramanujam [75] noted that XFOIL-like methods under predict drag for thick airfoils used in wind turbines, with errors reaching up to 30%. An improved drag formulation, now implemented in XFOIL and RFOIL by the Energy Research Centre of the Netherlands, accurately predicts drag by considering the difference between the momentum loss thickness at freestream velocity and at the boundary layer edge as predicted in Figure 22 [76].

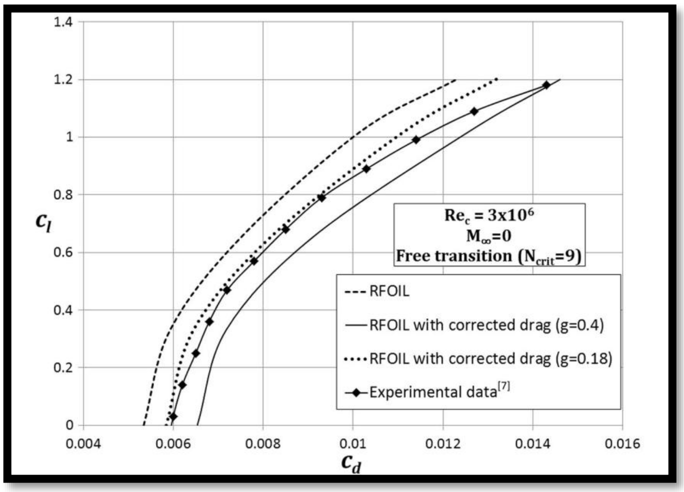

Figure 22: Predicted lift–drag polars for NACA 0012 in RFOIL

The method aligns well with experimental data and computational results from tools like ANSYS CFX and EllipSys2D. Byung-Young Min [77] presented RANS simulations for circulation control airfoils, highlighting that higher-order spatial accuracy had minimal impact on fine grid simulations and that two-equation turbulence models outperformed one-equation models. Inclusion of jet plenum chambers and nozzles allowed for detailed flow physics, though with little effect on overall loads. Mark D. Maughmer [78] [79] designed a high-altitude, long-endurance airfoil optimized for high lift coefficients at low Reynolds numbers, maintaining performance despite surface contamination, and demonstrating low drag across a range of lift coefficients. V.I. Kornilov [76] explored combined air blowing and suction for turbulent boundary layer control on a 12% thick symmetric airfoil, with numerical and experimental results showing improved aerodynamic performance. Yunjia Yang et al. [80] [81] developed a modified variational autoencoder (VAE) for predicting airfoil flowfields under off-design conditions, incorporating physical-based loss functions to reduce prediction errors by 30% compared to traditional models. Neil S.A. Lopez et al. [82] used ANSYS CFX to study the effects of surface modifications on lift and drag for rotating cylinders, finding that roughening the surface reduces drag at high-speed ratios, while bumps are more effective at lower speeds. The study also showed that switching to a frustum-shaped cylinder increases lift, suggesting potential applications in wind energy generation [83].

4.2 Airfoil design optimization via inverse method:

Airfoil design optimization via the inverse method involves tailoring an airfoil's shape to achieve a desired aerodynamic performance by directly specifying target aerodynamic characteristics, such as pressure distributions or performance coefficients (CL and CD), rather than iterating through various geometrical configurations. In this approach, computational tools like computational fluid dynamics (CFD) are used in conjunction with optimization algorithms—such as genetic algorithms, neural networks, or adjoint-based methods—to iteratively adjust the airfoil geometry until the desired performance is achieved. The inverse design process starts with setting an objective, such as maximizing the lift-to-drag ratio or delaying flow separation, and then reverse-engineering the optimal airfoil shape that meets these criteria. Advanced techniques, including deep learning models, Conditional Generative Adversarial Networks (cGANs), and reinforcement learning, have been increasingly utilized to accelerate the design process, enhance prediction accuracy, and explore unconventional airfoil shapes that conventional methods might overlook. This method not only provides a direct route to performance optimization but also enables the exploration of innovative airfoil designs that can be fine-tuned for specific operational conditions, such as varying Reynolds numbers, angles of attack, and flow regimes, thereby improving the overall aerodynamic efficiency of aircraft, wind turbines, and other aerodynamic surfaces.

V. Kitsios et al. [84] conducted a numerical study on the NACA 0015 airfoil, examining boundary layer control using zero-net-mass-flux (ZNMF) jets to modify flow separation and enhance lift across different angles of attack. Tuck and Soria (2004) performed complementary water tunnel experiments, measuring lift and drag for various angles of attack (α). At α = 18°, where the maximum lift increase was recorded, flow visualization and PIV measurements were conducted. While 2D simulations aligned with force measurements in attached flows, deviations appeared beyond the stall angle (α ≈ 10°) [85]. A 3D LES simulation at α = 18° closely matched experimental data, showing similar flow behavior in the attached boundary layer region despite stall. The ZNMF jet steepened the velocity profile, reducing momentum thickness and delaying separation, though discrepancies in identifying optimal forcing frequency were noted. Abubker Fadl et al. [86] analyzed modified Gurney flaps on S823 and S822 airfoils from the NREL family. A Gurney flap positioned at 96% of the chord on the pressure side enhanced the lift coefficient while slightly reducing the drag coefficient, optimizing the lift-to-drag ratio by 97% for a flap length of 2% of the chord between 4° and 6° angles of attack. The transition from laminar to turbulent flow over the SD7003 airfoil at low angles of attack was studied using the spectral elements code Nek5000, revealing that the transition process was independent of wake flow, with the shedding process linked to von Kármán instability. Improvements in 3D flow characteristics in low-pressure turbines were explored through endwall contouring and airfoil design modifications, reducing secondary flow structures and enhancing efficiency. A study on the Eppler 387 airfoil examined surface modifications for improved aerodynamic efficiency, with the L50c50t30d airfoil showing superior performance in subsonic flow at a Reynolds number of 2×10^5. [86]

Surface modifications on the NACA0012 airfoil, such as semicircular, V-shaped, and square dimples placed at 75% of the chord length, improved lift and reduced drag at a Reynolds number of 3.0×10^6, with semicircular dimples enhancing the lift coefficient by 11% and reducing drag by 3%. Natural laminar flow technology aimed at drag reduction through passive laminar flow control (LFC) was investigated using the dual N-factor method to predict boundary-layer transitions, achieving a 30% drag reduction on the RAE 2822 airfoil. For the FX63–137 airfoil, a deep learning model was developed to optimize pressure distributions in Figure 23, achieving over an 18% increase in the lift-to-drag ratio [87].

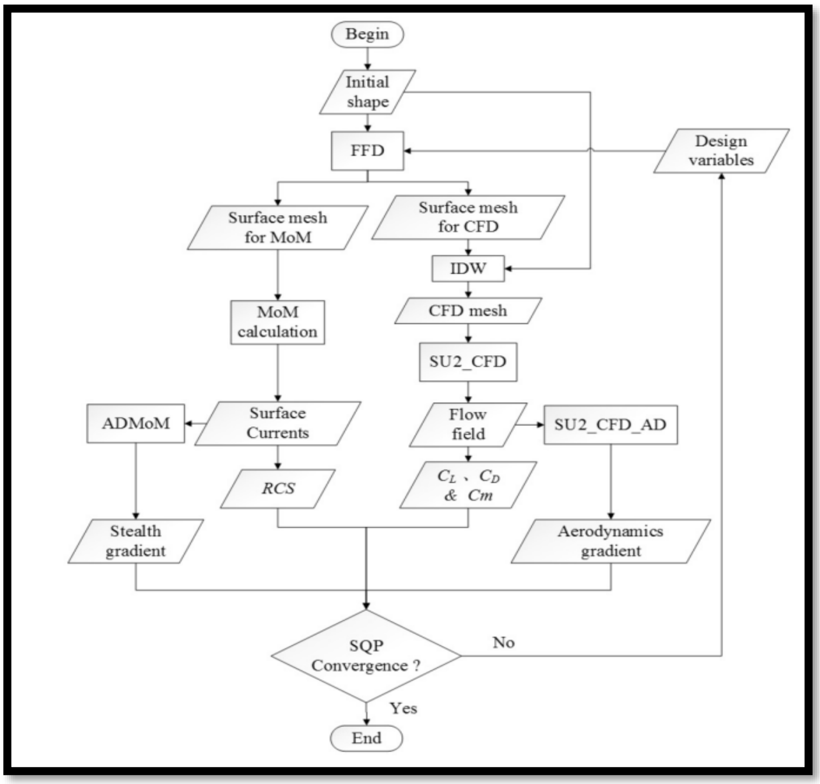

Figure 23: Flow chart of the aero-stealth optimization design method.

A Conditional Generative Adversarial Network (cGAN) approach introduced a two-step optimization technique using CST-cGANs, with a secondary optimization significantly enhancing geometric precision. Reinforcement learning inverse design (RLID) was employed to create a morphing airfoil adaptable to changing operational conditions, with a deep Q network (DQN) facilitating morphing in eight degrees of freedom, outperforming cGAN approaches. The Busemann supersonic biplane aerofoil was analyzed for its wave drag reduction capabilities through shock interactions, with robust design optimization (RDO) using the divided inexpensive Monte Carlo simulation (IMCS) method, yielding designs more resilient than the original Busemann configuration while balancing performance and robustness [88].

To maximize turbomachinery efficiency, optimizing airfoil designs is crucial for minimizing drag and maximizing lift while adhering to structural constraints. This study introduces a novel algorithm utilizing unconstrained conjugate gradient techniques to optimize the aerodynamic shapes of the NACA4412 and NACA2415 airfoils. The design variables are defined using Bézier parameterization, and optimization is performed with MATLAB and the XFOIL panel method. The results demonstrate performance improvements of 13.7% for the NACA4412 and 32% for the NACA2415 in terms of the lift-to-drag ratio and reduced angle of attack, highlighting the effectiveness of the proposed methodology over conventional techniques [83]. Additionally, an unconstrained spectral conjugate-gradient optimization technique was applied to further enhance aerodynamic shapes, utilizing control points and Bézier curves for parameterization, with the aim of reducing drag coefficients. This optimization approach consistently increased the lift-to-drag ratio while lowering the angle of attack, allowing optimized airfoils to achieve higher lift at reduced drag levels, thereby enhancing fuel efficiency and reducing structural stress during cruising [89]. A proposed airfoil inverse design method specifically targeted pressure gradient distribution by calculating derivatives using the adjoint approach, aiming to minimize the weighted drag coefficient while maintaining a specified lift coefficient. For the supercritical RAE2822 airfoil, the method proved effective, with a target pressure gradient of $c_{p,x}$ = 0.20 yielding consistent performance across various Mach numbers, demonstrating the potential of this optimization strategy in reducing design iterations and achieving optimal aerodynamic performance.[90,91]

The optimization techniques discussed demonstrate significant potential for improving airfoil performance, enhancing aerodynamic efficiency, and reducing drag across various operational conditions. Experimental data for the RAE2822 airfoil strongly supports the computational approach used in this study, with the effectiveness assessed through two inverse design test cases: a supercritical airfoil and a supercritical natural laminar flow (NLF) airfoil. The method successfully created high-performance airfoils using fewer than 20 target pressure points on the upper surface and fewer than 10 on the lower surface, achieving acceptable pressure distribution and low aerodynamic drag, validated by the transition model for the supercritical NLF airfoil. A multipoint inverse airfoil design technique for incompressible potential flow is also introduced, segmenting the airfoil into multiple sections with specified velocity distributions and angles of attack, and meeting several integral constraints, including thickness ratios and pitching moments, solved using multidimensional Newton iteration [92]. The inverse design method allows for specifying the velocity distribution, boundary-layer development, and surface geometry across various airfoil sections, addressing uncertainties in stopping calculations through an active subspace optimization technique that combines evolutionary algorithms with sparse polynomial approximations to yield ideal load distributions, resulting in a 3.6% reduction in total pressure loss coefficient compared to the initial solution. Furthermore, the airfoil wall is modeled as an elastic curved beam using an improved elastic surface algorithm (ESA), allowing controlled movement of the leading edge within a vertical groove and facilitating angle of attack adjustments during design. This approach was validated in the inverse design of FX63-137 and NACA0012 airfoils, achieving nearly a 4% increase in the lift-to-drag ratio by optimizing pressure distribution to improve lift or reduce drag [93,94].

4.3 Modification using Leading edge cylinder and Vortex generator:

In recent aerodynamic advancements, the integration of leading-edge cylinders and vortex generators on airfoils has emerged as a promising strategy to enhance lift and delay stall. These modifications manipulate airflow to increase turbulence and energy in the boundary layer, which can lead to improved lift coefficients and overall aerodynamic performance, particularly at lower speeds and higher angles of attack. Such technologies are proving crucial in optimizing the efficiency of various applications, from wind turbines to aircraft wings, by enhancing flow control and reducing aerodynamic losses [95].

Md Abdus Salam et al. enhanced the aerodynamic performance of the NACA 0021 airfoil by integrating a rotating leading-edge cylinder [96]. This modification strategically injected momentum into the upper surface boundary layer, delaying stall and improving lift, drag, and stall angle across various velocity ratios and angles of attack. The modified airfoil outperformed the base airfoil in lift and drag, particularly at velocity ratios above 0.356 and 0.7, respectively. The stall angle of attack nearly doubled at a ratio of 1.78. This cost-effective modification holds significant potential for applications like low-speed aircraft wings [97], wind turbine blades, and hydrofoils, where improved aerodynamic efficiency is crucial [98]. A computational study explored the aerodynamics of a modified NACA-0010 airfoil with a rotating cylinder at the leading edge. Results showed significant lift improvement, defying traditional expectations of zero lift at zero angle of attack. Further analyses revealed that adding a rotating cylinder increased lift, albeit with a slight rise in drag [99]. Another study investigated a passive flow control method using a micro-cylinder near the S809 airfoil, aiming to optimize lift-to-drag ratio [100]. Findings indicated that the micro-cylinder placement notably enhanced lift-to-drag ratio, particularly at higher Reynolds numbers and angles of attack, with slight diminishing effects at lower velocities. Both studies highlight innovative approaches to enhance aerodynamic performance through modifications at the leading edge [101]. Detecting and controlling vortex shedding in turbulent airfoil flows can enhance aerodynamic performance. A non-dimensional measure called the leading-edge suction parameter (LESP) is proven useful for identifying vortex shedding events from unstable airfoils. The leading-edge flow sensing (LEFS) approach [102], which uses a few pressures in the airfoil leading-edge region, helps infer LESP variations during unstable motions in incompressible flow [103]. This method divides the airflow into two regions: an inner-region flow over the leading edge and an outer-region flow over the chord [104]. By matching these flows, relations for computing LESP from leading-edge pressures are derived. Three criteria—initiation, pinch-off, and termination—are proposed for identifying vortex shedding events based on fluctuations in LEFS outputs and computed LESP values during different unstable motions [105]. Computational and experimental results validate LEFS as a sensor for vortex shedding events on unsteady airfoils [106]. Chaitanya Agarwal et al. analyzed the aerodynamic performance of the NACA0012 airfoil using CFD, comparing results with and without vortex generators (VG) [107] [108]. They found that the airfoil with VG exhibited improved lift and reduced drag coefficients, delaying stall up to 15° compared to the airfoil without VG[109]. Zidhane Aliffaputra Nuranto et al. further investigated the effects of gothic vortex generators on the NACA 2412 airfoil using CFD. Their analysis revealed that VG delayed airflow separation, with the best performance observed when VG were positioned at 15% chord length from the leading edge [110]. Both studies highlight the efficacy of vortex generators in enhancing aerodynamic performance by delaying stall and improving lift coefficients [111].

Vortex Generators (VGs) are widely used by the wind turbine industry, to control the flow over blade sections. Niels N. Sørensen et al. developed a computational fluid dynamic procedure capable of handling geometrically resolved vortex generators (VGs) on airfoil sections [112]. They applied this method to the FFAW3-301 and FFA-W3-360 airfoils at a Reynolds number of 3 million, comparing computations with wind tunnel measurements to assess lift and drag variation with angle of attack. [113] Additionally, Samridh Patial et al. investigated the effect of cavities on airflow over aerofoils at low Reynolds numbers using vortex shading methods. They observed an increase in lift coefficient for the NACA 0012 aerofoil under certain cavity parameters [114]. Furthermore, G. Balaji et al. [115] conducted a wind tunnel experiment to explore the impact of vortex generators on the aerodynamic characteristics of the NREL 2809 airfoil. Their study revealed pressure distribution variations with different vortex generator configurations, showing that the rectangular vortex generator induces greater pressure variation compared to the triangular vortex generator [116]. Siti et al. [117] investigated the impact of vortex generators (VGs) on the aerodynamics of the NACA-4412 airfoil using computational fluid dynamics. Placed on the upper surface at 24% from the leading edge, VGs transition airflow from laminar to turbulent, enhancing lift by resisting adverse pressure gradients. Variations in angle of attack (0°, 5°, 10°, 15°) demonstrated that straight-type VGs elevate lift coefficients. At 5° angle of attack, the airfoil with VGs showed significantly improved lift as shown in Figure 24.

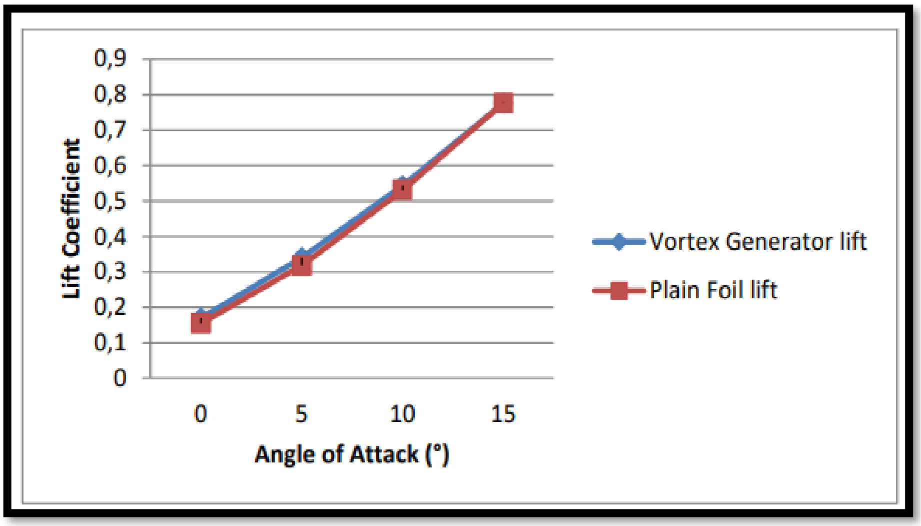

FIGURE 24: LIFT COEFFICIENT VS AOA. [75]

These VGs inject energy, delaying flow separation and potentially preventing stall by withstanding adverse pressure gradients. Rapid air dispersal results in increased lift force, directly correlating with angle of attack increments. Simulations showed notable lift coefficient increases with VGs at 5° angle of attack compared to plain airfoil configurations [118].

In conclusion, numerical studies investigating airflow over airfoils by varying angle of attack, and incorporating leading edge cylinders and vortex generators, have provided valuable insights into aerodynamic performance enhancement. By systematically varying the angle of attack, researchers have demonstrated the effects on lift, drag, and stall characteristics, highlighting the importance of optimizing aerodynamic configurations for improved efficiency [119], [120]. Additionally, the integration of leading edge cylinders and vortex generators has shown promising results in delaying stall, increasing lift coefficients, and resisting adverse pressure gradients [121], [122], [123]. These findings underscore the significance of innovative aerodynamic modifications in optimizing airfoil performance across various applications, from aircraft wings to wind turbine blades.

TABLE 2: NUMERICAL STUDIES

REFRENCE	TYPE OF MODIFICATION	MOFICATION PARAMETER	COMMENT
C PRANESH, M SIVAPRAGASAM*, M D DESHPANDE and H K NARAHARI [56]	Computational investigations on the flow over NACA 0012	Reynolds number	Identification of unusual lift characteristics at low Reynolds numbers for NACA 0012 aerofoil - Determination of a narrow range of parameters leading to negative lift at positive angles of attack - Identification of five flow regimes
Mariza D. Ardany1 , Paken Pandiangan2 and Moh. Hasan3 [58]	Computational Fluid Dynamics Simulation of NACA Airfoils with Different Cambers	Lift force, angle of attack and camber alteration	Greater angle of attack increases force lift (FL), but excessive angle of attack may lead to airfoil stall - NACA 6612 airfoil produces greatest maximum lift force at angle of attack 16° and flow rate 100 m/s

S Max, H Hamdani - Acta Mechanica Sinica [48]	Aerodynamic Force and Flow Structure of NACA 0012 Airfoil at Low Reynolds Number	Calculation of aerodynamic forces	Calculation of aerodynamic forces and flow structures during unsteady motion consisting of translation, rotation, and reverse translation of NACA 0012 airfoil
E. N. Jacobs, K. E. Ward, & R. M. Pinkerton [52]	Airfoils with modified nose shapes	Nose Shape Modification	The leading-edge radius significantly influences the maximum lift, especially when the radius is small.
E. N. Jacobs, K. E. Ward, & R. M. Pinkerton [52]	Airfoils with modified nose shapes	Airfoils with flexed mean line	The leading-edge radius significantly influences the maximum lift, especially when the radius is small.
E. N. Jacobs, K. E. Ward, & R. M. Pinkerton [52]	Airfoils with modified nose shapes	Thickness and camber modifications near the trailing edge	The leading-edge radius significantly influences the maximum lift, especially when the radius is small.
M YILMAZ, H KÖTEN, E Çetinkaya [53]	Computational fluid dynamics (CFD) analysis, ANSYS Fluent simulation	Angle of attack	Determination of optimal attack angles for NACA0012 and NACA4412 airfoils
Omar Madani Fouatiha,∗ , Marc Medale b , Omar Imine a , Bachir Imine [55]	Optimization of NACA 4415	Vortex generator optimization	Triangular-shaped vortex generators found to be best suited for controlling boundary layer separation
N F Zulkefli, M A Ahamat, N F Mohd Safri, N Mohd Nur, A S Mohd Rafie [54]	Lift Enhancement of NACA 4415	Vortex generator	- Identification of highest lift coefficient and highest drag coefficient for airfoil with shark skin shape vortex generator at high angles of attack
V. Kitsios†, R. B. Kotapati‡, R. Mittal‡, A. Ooi†, J.Soria¶ AND D. You [50]	Numerical simulation of lift enhancement on a NACA 0015	Net mass flux	Validation of 2-D and 3-D numerical simulations with water tunnel experiments for lift enhancement on NACA 0015 airfoil on NACA

V.CONCLUSION

The review highlights the multifaceted approaches employed in enhancing the aerodynamic efficiency of airfoils. Experimental studies, such as those investigating the effects of leading-edge slats and active flow control devices, provide valuable insights into real-world performance [1], [4]. Theoretical analyses contribute theoretical frameworks for understanding underlying aerodynamic principles and designing innovative solutions. Furthermore, numerical studies offer detailed simulations and optimization strategies, enabling a deeper understanding of airflow phenomena and the development of advanced airfoil designs [48], [52]. Together, these diverse approaches showcase the breadth and depth of research aimed at improving airfoil efficiency, paving the way for enhanced performance in various applications, from aviation to renewable energy.

Table 3: Optimized Cl/CD and Angle of Attack for different airfoils

Airfoil	Original C_l/C_d	Optimized C_l/C_d	Iterations	Difference %	Original AOA	Optimized AOA
NACA4412	107.87	122.7	5	14	6	4
NACA2415	87.1	115.42	5	32	5.75	5.15

Airfoil	Original C_l/C_d	Optimized C_l/C_d	Iterations	Difference %	Original AOA	Optimized AOA
NACA0010	55.2	68.24	6	24	4.25	4.15
NACA4418	93.3	119.59	10	28	6.5	5.02
NACA1408	66.6	97.90	9	47	3.25	2.75

VI.FUTURE RECOMMENDATION

Considering the literature review, the following future research is recommended:

- Investigate novel active flow control techniques, such as plasma actuators or synthetic jets, for fine-tuned manipulation of airflow over airfoils.
- Further research on bio-inspired aerodynamic concepts, such as biomimetic surfaces or morphing structures, to mimic nature's efficient aerodynamic designs.
- Investigate multi-disciplinary approaches integrating aerodynamics with materials science, structural mechanics, and propulsion systems to achieve holistic performance improvements.
- Explore additive manufacturing techniques for rapid prototyping and customization of complex airfoil geometries, facilitating iterative design optimization processes.
- Conduct wind tunnel experiments at higher Reynolds numbers and under realistic operating conditions to validate theoretical predictions and numerical simulations more rigorously.
- Develop advanced computational models incorporating high-fidelity simulations and machine learning algorithms to optimize airfoil designs with greater accuracy and efficiency.

Declaration of Competing Interest:
The authors declare that thy have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Aftab, S.M. and Ahmed, K.A., 2019. NACA 4415 Airfoil Modification Using Spherical and Sinusoidal Tubercle Leading Edge. In AIAA SciTech 2019 Forum (p. 0849).

[2] Rostamzadeh, N., Hansen, K.L., Kelso, R.M. and Dally, B.B., 2014. The formation mechanism and impact of streamwise vortices on NACA 0021 airfoil's performance with undulating leading edge modification. Physics of Fluids, 26(10)

[3] Katam, V., 2005. Simulation of low-Re flow over a modified NACA 4415 airfoil with oscillating camber.

[4] Smith, D., Amitay, M., Kibens, V., Parekh, D. and Glezer, A., 1998, August. Modification of lifting body aerodynamics using synthetic jet actuators. In 36th AIAA Aerospace Sciences Meeting and Exhibit (p. 209)

[5] Raghunathan, S. and Tan, C.P., 1985. Effect of blade profile on the performance of the Wells self-rectifying air turbine. International journal of heat and fluid flow, 6(1), pp.17-22

[6] Aziz, M.A.B. and Islam, M.S., 2017. Effect of lower surface modification on aerodynamic characteristics of an airfoil. In International Conference on Mechanical Engineering and Renewable Energy.

[7] Ethiraj, L. and Pillai, S.N., 2021. Effect of trailing-edge modification over aerodynamic characteristics of NACA 0020 airfoil. Wind and Structures, 33(6), pp.463-470.

[8] Jones, R., J. Doolan, C. and Teubner, M., 2011, June. Minimization of trailing edge noise by parametric airfoil shape modifications. In 17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference) (p. 2782).

[9] Sogukpinar, H., 2018, February. The effects of NACA 0012 airfoil modification on aerodynamic performance improvement and obtaining high lift coefficient and post-stall airfoil. In AIP conference proceedings (Vol. 1935, No. 1). AIP Publishing.

[10] Singh, D., Manik, M.K., Rao, P.S. and Ansari, A.H., 2019. ―Performance of Aerodynamic Characteristics of different shapes of NACA aerofoil‖. CCET Journal of Science and Engineering Education, 4, pp.71-76.

[11] Sherman, A., 1939. Preliminary report on the characteristics of the NACA 4400R series airfoils (No. NACA-WR-L-451).

[12] Harris, C.D. and Blackwell Jr, J.A., 1972. Wind-tunnel investigation of effects of rear

upper surface modification on a NASA supercritical airfoil (No. NASA-TM-X-2454).
[13] Oxford, V.S. and AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING, 1975. A Wind Tunnel Study of the Effects of Trailing Edge Modifications on the Lift-Drag Ratio of a Circulation Controlled Airfoil (Doctoral dissertation, Air Force Institute of Technology).
[14] Bénard, N., Jolibois, J. and Moreau, E., 2009. Lift and drag performances of an axisymmetric airfoil controlled by plasma actuator. Journal of Electrostatics, 67(2-3), pp.133-139.
[15] Tsao, J.C. and Lee, S., 2012. Evaluation of icing scaling on swept NACA 0012 airfoil models (No. E-18090).
[16] Douvi, E. and Margaris, D., 2011, July. Simulation of heavy rain flow over a NACA 0012 airfoil. In Proceedings of the 4th International Conference on Experiments/Process/System Modeling/Simulation/Optimization (4th IC-EpsMsO), Athens, Greece (pp. 6-9).
[17] Genç, M.S., Karasu, İ. and Açıkel, H.H., 2012. An experimental study on aerodynamics of NACA2415 aerofoil at low Re numbers. Experimental Thermal and Fluid Science, 39, pp.252-264.
[18] Bhat, S.S. and Govardhan, R.N., 2013. Stall flutter of NACA 0012 airfoil at low Reynolds numbers. Journal of Fluids and Structures, 41, pp.166-174.
[19] Spaid, F., Dahlin, J., Roos, F. and Stivers, L., 1983. Static Pressure and Drag Data Obtained from Tests of a Supercritical Airfoil and an NACA 0012 Airfoil at Transonic Speeds. NASA TM-81336.
[20] Zhou, T. and Dowell, E., 2014, November. Buffeting of NACA 0012 airfoil at high angle of attack. In APS Division of Fluid Dynamics Meeting Abstracts (pp. M30-001).
[21] Hossain, S., Raiyan, M.F., Akanda, M.N.U. and Jony, N.H., 2014. A comparative flow analysis of NACA 6409 and NACA 4412 aerofoil. International Journal of Research in Engineering and Technology, 3(10), pp.342-350.
[22] Ismail, M.F. and Vijayaraghavan, K., 2015. The effects of aerofoil profile modification on a vertical axis wind turbine performance. Energy, 80, pp.20-31.
[23] Siauw, W.L., Bonnet, J.P., Tensi, J., Cordier, L., Noack, B.R. and Cattafesta, L., 2010. Transient dynamics of the flow around a NACA 0015 airfoil using fluidic vortex generators. International Journal of Heat and Fluid Flow, 31(3), pp.450-459.
[24] Nahar, N., Sharma, M., Jha, A.K. and Joshi, R., 2023. AERODYNAMIC ANALYSIS OF RAMP TYPE VORTEX GENERATOR ON NACA 2215 AIRFOIL. surfaces, 10(06)
[25] Chillon, S., Uriarte-Uriarte, A., Aramendia, I., Martínez-Filgueira, P., Fernandez-Gamiz, U. and Ibarra-Udaeta, I., 2020. jBAY modeling of vane-type vortex generators and study on airfoil aerodynamic performance. Energies, 13(10), p.2423.
[26] Li, X., Yang, K. and Wang, X., 2019. Experimental and numerical analysis of the effect of vortex generator height on vortex characteristics and airfoil aerodynamic performance. Energies, 12(5), p.959.
[27] Arunvinthan, S., Raatan, V.S., Nadaraja Pillai, S., Pasha, A.A., Rahman, M.M. and Juhany, K.A., 2021. Aerodynamic characteristics of shark scale-based vortex generators upon symmetrical airfoil. Energies 14.
[28] Kundu, P., Sarkar, A. and Nagarajan, V., 2019. Improvement of performance of S1210 hydrofoil with vortex generators and modified trailing edge. Renewable Energy, 142, pp.643-657.
[29] Cai, C., Liu, S., Zuo, Z., Maeda, T., Kamada, Y., Li, Q.A. and Sato, R., 2019. Experimental and theoretical investigations on the effect of a single leading-edge protuberance on airfoil performance. Physics of Fluids, 31(2).
[30] Santana, L.D., Christophe, J., Schram, C. and Desmet, W., 2016. A rapid distortion theory modified turbulence spectra for semi-analytical airfoil noise prediction. Journal of sound and vibration, 383, pp.349-363.
[31] Suzuki, H., Rinoie, K. and Tezuka, A., 2010. Laminar airfoil modification attaining optimum drag reduction by use of airfoil morphing. Journal of aircraft, 47(4), pp.1126-1132.
[32] Tang, Z. and Huang, M., 2001. Control theory-based airfoil design using Euler equations. Acta Aerodynamica Sinica, 19(3), pp.262-270.
[33] Ramesh, K., Gopalarathnam, A., Edwards, J.R., Ol, M.V. and Granlund, K., 2013. An unsteady airfoil theory applied to pitching motions

validated against experiment and computation. Theoretical and Computational Fluid Dynamics, 27, pp.843-864.
[34] Martins, A.L. and Catalano, F.M., 1996. Theoretical Study of a Mission Adaptive Wing. In ICAS PROCEEDINGS (Vol. 20, pp. 725-732).
[35] Hariharan, N. and Leishman, J.G., 1996. Unsteady aerodynamics of a flapped airfoil in subsonic flow by indicial concepts. Journal of Aircraft, 33(5), pp.855-868.
[36] Lee, Y.T., Gementzopoulos, A., Chitrala, N., Suresh Babu, A.V., Jones, A. and Gopalarathnam, A., 2023. Combined Theoretical and Experimental Investigation of Airfoil Encountering Transverse Gust. In AIAA AVIATION 2023 Forum (p. 4012).
[37] Beri, H. and Yao, Y., 2011, March. Computational analysis of vertical axis wind turbine with open-able airfoil. In 2011 Asia-Pacific Power and Energy Engineering Conference (pp. 1-5). IEEE.
[38] Chen, W., Qiao, W. and Wei, Z., 2020. Aerodynamic performance and wake development of airfoils with wavy leading edges. Aerospace Science and Technology, 106, p.106216.
[39] Loftin Jr, L.K., 1946. Theoretical and experimental data for a number of NACA 6A-series airfoil sections (No. NACA-RM-L6J01).
[40] Somers, D.M., 1997. Design and experimental results for the S809 airfoil (No. NREL/SR-440-6918). National Renewable Energy Lab.(NREL), Golden, CO (United States).
[41] Hongpeng, L., Yu, W., Rujing, Y., Peng, X. and Qing, W., 2020. Influence of the modification of asymmetric trailing-edge thickness on the aerodynamic performance of a wind turbine airfoil. Renewable energy, 147, pp.1623-1631.
[42] Coder, J.G., Maughmer, M.D. and Somers, D.M., 2014. Theoretical and experimental results for the S414, slotted, natural-laminar-flow airfoil. Journal of Aircraft, 51(6), pp.1883-1890.
[43] Yossri, W., Ayed, S.B. and Abdelkefi, A., 2021. Airfoil type and blade size effects on the aerodynamic performance of small-scale wind turbines: Computational fluid dynamics investigation. Energy, 229, p.120739
[44] Raghunathan, S. and Tan, C.P., 1985. Effect of blade profile on the performance of the Wells self-rectifying air turbine. International journal of heat and fluid flow, 6(1), pp.17-22.
[45] Johnson, S. J., Baker, J. P., & Berg, D. (2010). An overview of active load control techniques for wind turbines with an emphasis on microtabs. Wind Energy, 13(2-3), 239-253. https://doi.org/10.1002/we.356
[46] Zhang, M.M., Wang, G.F. and Xu, J.Z., 2013. Aerodynamic control of low-Reynolds-number airfoil with leading-edge protuberances. AIAA journal, 51(8), pp.1960-1971.
[47] He, W. and Liu, X., 2019. Improved aerofoil parameterisation based on class/shape function transformation. The Aeronautical Journal, 123(1261), pp.310-339.
[48] Zhu, C., Chen, J., Wu, J. and Wang, T., 2019. Dynamic stall control of the wind turbine airfoil via single-row and double-row passive vortex generators. Energy, 189, p.116272.
[49] Zhang, X., Li, W. and Kong, C., 2014. Effect of relative thickness on improving airfoil aerodynamic performance by blunt trailing-edge modification. Advances in Mechanical Engineering, 2014.
[50] Luo, J., Xiong, J. and Liu, F., 2014. Aerodynamic design optimization by using a continuous adjoint method. SCIENCE CHINA Physics, Mechanics & Astronomy, 57, pp.1363-1375.
[51] Park, H., Lee, D., Jeon, W.P., Hahn, S., Kim, J., Kim, J., Choi, J.I.N. and Choi, H., 2006. Drag reduction in flow over a two-dimensional bluff body with a blunt trailing edge using a new passive device. Journal of Fluid Mechanics, 563, pp.389-414.
[52] Ockfen, A. E., & Matveev, K. I. (2009). Aerodynamic characteristics of NACA 4412 airfoil section with flap in extreme ground effect. International Journal of Naval Architecture and Ocean Engineering, 1(1), 1-12. https://doi.org/10.2478/IJNAOE-2013-0001
[53] Barrett, R. and Ning, A., 2016. Comparison of airfoil precomputational analysis methods for optimization of wind turbine blades. IEEE Transactions on Sustainable Energy, 7(3), pp.1081-1088.
[54] Rogowski, K., Hansen, M.O.L. and Bangga, G., 2020. Performance analysis of a H-Darrieus wind turbine for a series of 4-digit NACA airfoils. Energies, 13(12), p.3196.

[55] YILMAZ, M., KÖTEN, H., Çetinkaya, E. and Coşar, Z., 2018. A comparative CFD analysis of NACA0012 and NACA4412 airfoils. Journal of Energy Systems, 2(4), pp.145-159.

[56] Qu, Q., Jia, X., Wang, W., Liu, P. and Agarwal, R.K., 2014. Numerical study of the aerodynamics of a NACA 4412 airfoil in dynamic ground effect. Aerospace Science and Technology, 38, pp.56-63.

[57] Mukhti, Muhammad Ammar Qayyum Abdul, et al. "Computational fluid dynamic simulation study on NACA 4412 airfoil with various angle of attacks." Journal of Design for Sustainable and Environment 3.1 (2021).

[58] Eggert, Christopher A., and Christopher L. Rumsey. CFD study of NACA 0018 airfoil with flow control. No. NASA/TM-2017-219602. 2017.Eggert, Christopher A., and Christopher L. Rumsey. CFD study of NACA 0018 airfoil with flow control. No. NASA/TM-2017-219602. 2017.

[59] Akhil, Yuvaraj & Jithendra Sai Raja, Chada & Surapaneni, Sambhu & Geeri, Satish. (2020). Flow behavior on aerofoils using CFD. Journal of Mechanical Engineering, Automation and Control Systems. 1. 26-36. 10.21595/jmeacs.2020.21515.

[60] Islam Rubel R, Kamal Uddin M, Zahidul Islam M, Rokunuzzaman M. Numerical and Experimental Investigation of Aerodynamics Characteristics of NACA 0015 Aerofoil. IJET. 2017;2(4):132-41.

[61] Zhang, Z., 2022. Unsteady Aerodynamics of Wings in Turbulent Wakes (Doctoral dissertation, PhD Thesis, University of Bath (to be submitted)).

[62] Mani, M. and Dorgan, A.J., 2023. A perspective on the state of aerospace computational fluid dynamics technology. Annual Review of Fluid Mechanics, 55, pp.431-457.

[63] Menier, V., 2015. Numerical methods and mesh adaptation for reliable RANS simulations (Doctoral dissertation, Université Pierre et Marie Curie-Paris VI).

[64] Spentzos, A., Barakos, G.N., Badcock, K.J., Richards, B.E., Coton, F.N., Galbraith, R.M., Berton, E. and Favier, D., 2007. Computational fluid dynamics study of three-dimensional dynamic stall of various planform shapes. Journal of Aircraft, 44(4), pp.1118-1128.

[65] Aeschliman, D.P. and Oberkampf, W.L., 1998. Experimental methodology for computational fluid dynamics code validation. AIAA journal, 36(5), pp.733-741.

[66] Li, D., 2007. Numerical simulation of thin airfoil stall by using a modified DES approach. International journal for numerical methods in fluids, 54(3), pp.325-332.

[67] Vadillo, J., Agarwal, R., Cary, A. and Bower, W., 2003. Numerical study of virtual aerodynamic shape modification of an airfoil using a synthetic jet actuator. In 33rd AIAA Fluid Dynamics Conference and Exhibit (p. 4158).

[68] Van Rooij, R.P.J.O.M., 1996. Modification of the boundary layer calculation in RFOIL for improved airfoil stall prediction.

[69] Sreejith, B.K. and Sathyabhama, A., 2020. Experimental and numerical study of laminar separation bubble formation on low Reynolds number airfoil with leading-edge tubercles. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42(4), p.171.

[70] Hongpeng, L., Yu, W., Rujing, Y., Peng, X. and Qing, W., 2020. Influence of the modification of asymmetric trailing-edge thickness on the aerodynamic performance of a wind turbine airfoil. Renewable Energy, 147, pp.1623-1631.

[71] Gardner, A.D., Richter, K. and Rosemann, H., 2011. Numerical investigation of air jets for dynamic stall control on the OA209 airfoil. CEAS Aeronautical Journal, 1, pp.69-82.

[72] Winslow, J., Otsuka, H., Govindarajan, B. and Chopra, I., 2018. Basic understanding of airfoil characteristics at low Reynolds numbers (10 4–10 5). Journal of aircraft, 55(3), pp.1050-1061.

[73] Ramanujam, G., Özdemir, H. and Hoeijmakers, H.W.M., 2016. Improving airfoil drag prediction. Journal of Aircraft, 53(6), pp.1844-1852.

[74] Min, B.Y., Lee, W., Englar, R. and Sankar, L.N., 2009. Numerical investigation of circulation control airfoils. Journal of Aircraft, 46(4), pp.1403-1410.

[75] Maughmer, M.D. and Somers, D.M., 1989. Design and experimental results for a high-altitude, long-endurance airfoil. Journal of Aircraft, 26(2), pp.148-153.

[76] Kornilov, V.I., Kavun, I.N. and Popkov, A.N., 2019. Modification of turbulent airfoil section flow using a combined control action.

Thermophysics and Aeromechanics, 26(2), pp.165-178.

[77] Yang, Y., Li, R., Zhang, Y. and Chen, H., 2022. Flowfield prediction of airfoil off-design conditions based on a modified variational autoencoder. AIAA Journal, 60(10), pp.5805-5820.

[78] Lopez, N.S., Mara, B.K., Mercado, B.C. and Pascual, J.M.G., 2015. Characterisation of the effects of surface modifications to flow across rotating cylinders using ANSYS CFD modelling. Chemical Engineering Transactions, 45, pp.1129-1134.

[79] Kitsios, V., Kotapati, R., Mittal, R., Ooi, A., Soria, J. and You, D., 2006. Numerical simulation of lift enhancement on a NACA 0015 airfoil using ZNMF jets. In Proceedings of the Summer Program (p. 457).

[80] Fadl, A., Abbasher, M., Younis, O.B.A.I. and El Seory, A., 2017. A numerical investigation of the performance of wind turbine airfoils with gurney flaps and airfoilshape alteration. J. Eng. Sci. Technol, 13, pp.1-16.

[81] Omer, E., 2023. ENHANCEMENT OF AIRFOIL AERODYNAMIC CHARACTERISTICS BY SURFACE MODIFICATIONS. University of Zawia Journal of Engineering Sciences and Technology, 1(1).

[82] Zhou, Q., Liu, H., Hou, W. and Duan, Y., 2024, May. Two-Step optimization based on CST-cGANs for airfoil inverse design. In Proceedings of the 2024 5th International Conference on Computing, Networks and Internet of Things (pp. 38-42).

[83] Van Rooij, R.P.J.O.M., 1996. Modification of the boundary layer calculation in RFOIL for improved airfoil stall prediction.

[84] Yuan, G., Lu, X. and Wei, Z., 2009. A conjugate gradient method with descent direction for unconstrained optimization. Journal of Computational and Applied Mathematics, 233(2), pp.519-530.

[85] Han, Z.H.; Chen, J.; Zhang, K.S.; Xu, Z.M.; Zhu, Z.; Song, W.P. Aerodynamic Shape Optimization of Natural-Laminar-Flow Wing Using Surrogate-Based Approach. AIAA J. 2018, 56, 2579–2593

[86] Zhang, Y., Yan, C. and Chen, H., 2020. An inverse design method for airfoils based on pressure gradient distribution. Energies, 13(13), p.3400

[87] Collazo Garcia III, A.R. and Ansell, P.J., 2024. Airfoil design framework for optimized boundary-layer integral parameters. Journal of Aircraft, pp.1-16.

[88] Shirvani, A., Nili-Ahmadabadi, M. and Ha, M.Y., 2024. A deep learning–genetic algorithm approach for aerodynamic inverse design via optimization of pressure distribution. Computer Methods in Applied Mechanics and Engineering, 429, p.117187.

[89] Zhou, Q., Liu, H., Hou, W. and Duan, Y., 2024, May. Two-Step optimization based on CST-cGANs for airfoil inverse design. In Proceedings of the 2024 5th International Conference on Computing, Networks and Internet of Things (pp. 38-42).

[90] Ducoin, A., Loiseau, J.C. and Robinet, J.C., 2016. Numerical investigation of the interaction between laminar to turbulent transition and the wake of an airfoil. European Journal of Mechanics-B/Fluids, 57, pp.231-248.

[91] Eymann, S., Reinmo¨ ller, U., Niehuis, R., Fo¨ rster, W., Beversdorff, M. and Gier, J., 2002, January. Improving 3D Flow Characteristics in a Multistage LP Turbine by Means of Endwall Contouring and Airfoil Design Modification: Part 1—Design and Experimental Investigation. In Turbo Expo: Power for Land, Sea, and Air (Vol. 3610, pp. 249-260).

[92] Spurthy, S., Sumukha, G.D., Prathik, B.V., Naveen, R., Srikanth, H.V. and Sridhar, K., 2020, January. Study on effect of surface modification on aerodynamic characteristics of Eppler 387 airfoil. In AIP Conference Proceedings (Vol. 2204, No. 1). AIP Publishing.

[93] Mrad, H. and Fakhari, S.M., 2024. Optimization of unconstrained problems using a developed algorithm of spectral conjugate gradient method calculation. Mathematics and Computers in Simulation, 215, pp.282-290.

[94] Fakhari, S.M. and Mrad, H., 2024. Aerodynamic Shape Optimization of NACA Airfoils Based on a Novel Unconstrained Conjugate Gradient Algorithm. Journal of Engineering Research.

[95] Zhang, Y.; Fang, X.; Chen, H.; Fu, S.; Duan, Z.; Zhang, Y. Supercritical Natural Laminar Flow Airfoil Optimization for Regional Aircraft Wing Design. Aerosp. Sci. Technol. 2015, 43, 152–164

[96] Li, J.; Gao, Z.; Huang, J.; Zhao, K. Robust Design of NLF Airfoils. Chin. J. Aeronaut. 2013, 26, 309–318
[97] Selig, M.S. and Maughmer, M.D., 1992. Multipoint inverse airfoil design method based on conformal mapping. AIAA journal, 30(5), pp.1162-1170
[98] Aminian, M. and Namjoo, M., 2024. Characteristics of T--conformal mappings. Journal of Finsler Geometry and its Applications, 5(1), pp.97-114.
[99] Chen, Y., Zheng, Q., Jiang, Y. and Jiang, B., 2024. Inverse design optimization of the compressor cascade airfoil assisted by active subspace approach. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, p.09576509241260795.
[100] Drafsh, Z., Nili-Ahmadabadi, M., Noorsalehi, M.H., Shirvani, A. and Ha, M.Y., 2024. Upgrade in the elastic surface algorithm for airfoil inverse design with variable attack angle via controlled leading-edge movement. Journal of Mechanical Science and Technology, pp.1-13.
[101] M. Safari, M. Nili-Ahmadabadi, A. Ghaei and E. Shirani, Inverse design in subsonic and transonic external flow regimes using elastic surface algorithm, Computers & Fluids, 102 (2014) 41–51
[102] Paredes, P., Mysore, P., Jacobson, K., Diskin, B., Hildebrand, N.J. and Choudhari, M.M., 2024. Aerodynamic Design Optimization for Natural Laminar Flow Airfoils. In AIAA AVIATION FORUM AND ASCEND 2024 (p. 3529).
[103] Li, M., Chen, J., Feng, X., Qu, F. and Bai, J., 2021. An efficient adjoint method for the aero-stealth shape optimization design. Aerospace Science and Technology, 118, p.107017.
[104] Wei Chen,Kevin Chiu,and Mark D Fuge.2020.Airfoil design parameterization and optimization using bezier generative adversarial networks.AIAA journal,58,11,4723-4735.
[105] Lingling, C.H.U., Qi, L.I., Feng, G.U., Xintian, D.U., Yuqing, H.E. and Yangchen, D.E.N.G., 2022. Design, modeling, and control of morphing aircraft: A review. Chinese journal of aeronautics, 35(5), pp.220-246.
[106] Su, J., Sun, G. and Tao, J., 2024. A novel inverse design method for morphing airfoil based on deep reinforcement learning. Aerospace Science and Technology, 145, p.108895.
[107] Ntantis, E.L. and Xezonakis, V., 2024. Aerodynamic design optimization of a NACA 0012 airfoil: An introductory adjoint discrete tool for educational purposes. International Journal of Mechanical Engineering Education, p.03064190241254020.
[108] He X, Li J, Mader CA, et al. Robust aerodynamic shape optimization—from a circle to an airfoil. Aerosp Sci Technol 2019; 87: 48–61.
[109] Salam, M.A., Deshpande, V., Panday, S., Khan, N.A. and Ali, M.A., 2019, July. Improvement in aerodynamic performance of NACA0021 airfoil using moving surface boundary layer: A computational study. In AIP Conference Proceedings (Vol. 2121, No. 1). AIP Publishing.
[110] Salam, M.A., Barman, S., Atique, M.S.A., Nafi, A.S., Probha, N.N. and Faisal, K.M., 2015, May. CFD approach to analyze the aerodynamics potentiality of rotary leading edge aircraft wing at different angle of attack. In 2015 International Conference on Electrical Engineering and Information Communication Technology (ICEEICT) (pp. 1-6). IEEE.
[111] Mostafa, W., Abdelsamie, A., Mohamed, M., Thévenin, D. and Sedrak, M., 2020, November. Aerodynamic performance improvement using a micro-cylinder as a passive flow control around the S809 airfoil. In IOP conference series: materials science and engineering (Vol. 973, No. 1, p. 012040). IOP Publishing.
[112] Saini, A., Narsipur, S. and Gopalarathnam, A., 2021. Leading-edge flow sensing for detection of vortex shedding from airfoils in unsteady flows. Physics of Fluids, 33(8).
[113] Agarwal, C., Prakash, R., Mahajan, V., Chhetri, A., Vinaygamurthy, G. and Bhushan, A., 2021, December. Investigation on the Influence of Vortex Generators on Aerofoil. In Conference on Fluid Mechanics and Fluid Power (pp. 263-270). Singapore: Springer Nature Singapore.
[114] Pambudiyatno, N., 2023, October. Analysis of the Effect of Gothic Vortex Generator Using Computational Fluid Dynamic on Naca 2412. In Proceedings of the International Conference on Advance Transportation, Engineering, and Applied Science (ICATEAS 2022) (Vol. 217, p. 26). Springer Nature

[115] Sørensen, N.N., Zahle, F., Bak, C. and Vronsky, T., 2014, June. Prediction of the effect of vortex generators on airfoil performance. In Journal of physics: conference series (Vol. 524, No. 1, p. 012019). IOP Publishing
[116] Patial, S., Jain, P., Rawat, P., Bodavula, A. and Yadav, R., 2020. The study of the effect of the cavity on the flow over NACA 0012 and Selig 7003 aerofoil at low Reynolds number using vortex shading method. In AIAA Scitech 2020 forum (p. 2218).
[117] Balaji, G., Catherine Victoria, P., Solaiyappan, G., Mano, R.T., Santhakumar, U., Santhosh Kumar, G., Singha, D. and Hassan Ansari, R.H.T., 2023, August. Effect of Pressure Distribution of NREL S809 Airfoil with Vortex Generator. In International Conference on Smart Sustainable Materials and Technologies (pp. 161-168). Cham: Springer Nature Switzerland.
[118] Ayudia, S.A., Arkundato, A. and Rohman, L., 2020. Study of Vortex Generator Effect on Airfoil Aerodynamics Using the Computational Fluids Dynamics Method. Computational And Experimental Research In Materials And Renewable Energy, 3(2), pp.68-74.
[119] ŞAHİN, M., SALTAN, M.A. and BAŞKAYA, B.B., 2023. Experimental and numerical investigation of different wing profiles. International Journal of Energy Studies, 8(2), pp.151-166.
[120] Wood, A., 2017. Aerodynamic Lift, Drag and Moment Coefficients| AeroToolbox.
[121] Hossain, M.A., Uddin, M.N., Mustak, R. and Mashud, M., 2015. Experimental study of aerodynamic characteristics of airfoils using different shaped dimples. The International Journal Of Engineering And Science (IJES), 4(1), pp.13-17.
[122] Kabir, A., Al-Obaidi, A.S.M. and Myan, F.W.Y., 2023, July. Review and aerodynamic analysis of NACA 2415 morphing wing for variable span and scale morphing concepts using CFD analysis. In Journal of Physics: Conference Series (Vol. 2523, No. 1, p. 012033). IOP Publishing.
[123] Series, N.F.D., 2012. The NACA airfoil series.