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Design, Optimization, and Determination of Lift and Drag forces of NACA Aerofoils for Enhanced Performance

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ABSTRACT

The National Advisory Committee for Aeronautics (NACA) aerofoil shapes are widely used in aviation for wings, tails, and rotor blades but face challenges such as low lift, high drag, and poor stall behavior, leading to increased fuel consumption and accident risks. This study analyzes and optimizes the aerodynamic performance of NACA 4415, 2412, and 0015 aerofoils using XFLR5, considering parameters like wingspan, chord length, and thickness. Computational Fluid Dynamics (CFD) analysis and optimization tools in XFLR5 were used to evaluate and enhance performance. Results show that the modified NACA 4415, with higher camber, achieved the highest lift coefficient (Cl = 1.472) with an 8.47% improvement, a 52.11% reduction in drag, and an optimized lift-to-drag ratio of 48.34 (135.8% improvement), making it ideal for high-lift applications such as small aircraft and model planes. NACA 2412, with moderate camber, demonstrated a balanced performance with a Cl of 1.259 (3.71% improvement), a 47.41% drag reduction, and the highest lift-to-drag ratio of 50.163 (122.93% improvement), making it suitable for light aircraft, sailplanes, and aerodynamic research. NACA 0015, a symmetric aerofoil, exhibited the lowest lift coefficient (Cl = 1.033, 16.07% increase), 47.31% drag reduction, and the lowest lift-to-drag ratio of 36.903 (74.06% improvement), making it suitable for applications such as helicopter rotors, wind turbine blades, and marine technologies. The optimization results, showing convergence for most angles of attack except at 0° for all aerofoils, likely due to numerical instability or insufficient flow separation data. Additionally, NACA 0015 fails to converge at $\alpha = 13°$ and $\alpha = 14°$ due to excessive flow separation and vortex shedding, leading to unsteady aerodynamic forces that cause divergence in the solution. NACA 4415 and NACA 2412, while generally stable, exhibit minor convergence issues at $\alpha = 14°$ and $\alpha = 15°$, respectively, likely due to the onset of stall, causing unsteady flow behavior. At $\alpha = 15°$, the simulation converges, but NACA 0015 shows a sharp drop in Cl (0.445) and a Cd increase (0.152), confirming high drag due to stall effects, limiting its aerodynamic efficiency at high α. These modifications significantly enhance aerodynamic efficiency, improving fuel economy and performance across various aviation and engineering applications.

1. Introduction

The National Advisory Committee for Aeronautics (NACA) aerofoil refers to a series of standardized aerodynamic shapes specifically developed to optimize aircraft performance. An aerofoil is the cross-sectional shape of a wing or the blades of a propeller, rotor, turbine, or sail, designed with curved surfaces to provide the most favourable ratio between lift and drag forces during flight. These NACA aerofoils are characterized by a numerical designation that conveys essential geometric and

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aerodynamic properties, allowing precise identification of their shape and performance characteristics. NACA standards are fundamental to aviation**,** playing crucial roles in the design of wings, tail sections, and propulsion components to ensure efficiency and aerodynamic stability [1].

NACA aerofoils face challenges such as low lift force, high drag force, high pitching moment, and poor stall behaviour due to design inefficiencies related to geometry parameters like lift force, Drag force and optimisation limitations. These issues are further exacerbated at lower Reynolds numbers below 10^5 [2]. While previous efforts, including aerofoil shape modifications and surface enhancements like dimples and riblets, have aimed to improve efficiency, they have not fully addressed these critical challenges. There is a pressing need for innovative design optimization strategies focusing on refining NACA aerofoil geometries and incorporating sustainable approaches to enhance aerodynamic performance, reduce drag, and improve lift efficiency.

Design optimization is a systematic approach to enhancing the performance of systems, components, or processes by adjusting design variables such as camber, position of camber, and thickness while meeting specific constraints and objectives. In the context of NACA aerofoils, optimization aims to improve aerodynamic metrics such as lift-to-drag ratio (C_l/C_d), drag coefficient (C_d), and lift coefficient (C_l) to suit specific applications. The process begins by defining objectives, such as maximizing C_l, C_l/C_d and minimizing C_d, by identifying relevant design variables like aerofoil shape, angle of attack (AoA), and flow conditions. Constraints, including structural and aerodynamic requirements, are established to ensure feasibility. Techniques such as gradient-based optimization, genetic algorithms (GAs), and Computational Fluid Dynamics (CFD) simulations are employed to iteratively refine the design [3]. The design optimization of efficient aerofoils is crucial in various engineering applications and the performance of aerofoils at low Reynolds numbers has garnered significant interest due to their critical role in various applications, including low-speed aircraft operations, aircraft wings, the design of Micro Air Vehicles (MAVs), Unmanned Aerial Vehicles (UAVs), compressor blades, wind turbine blades, inboard sections of helicopter rotor blades, and certain fixed-wing designs [4]. Understanding aerofoil behaviour under these conditions is essential for optimizing aerodynamic efficiency, reducing energy losses, and enhancing overall performance across these technologies [5].

Many researchers have focused on the design and development of NACA aerofoils. For instance,[6] investigated strategies to reduce drag force and increase lift force and velocity in aircraft with powerful engines, observing a 10% reduction in drag force. Ebadi *et al.* [7] highlighted advancements such as a 10% drag reduction and 37% weight reduction using composite materials, though many studies focus on surface modifications like dimples, riblets, and winglets, which may improve lift but don't fully address material limitations. For example, Dinesh *et al.* [8] used riblets to reduce drag by 5%, but the results were specific to certain Reynolds numbers and riblet sizes. Similarly, Rubiat [9], found that dimpled NACA 4415 aerofoil improved lift and delayed flow separation at higher angles of attack. However, NACA aerofoils also exhibit disadvantages, including low lift force, high drag force, and poor stall behavior caused by inefficient design, heavyweight, and flow separation. These issues result in higher fuel consumption, increased emissions, reduced speed, longer take-off times, and elevated flight costs. These combined effects significantly reduce aerodynamic efficiency [10].

2. Materials and Methods

2.1 Materials/Equipment

The following equipment was used in this research work include Computational Fluid Dynamics software (CFD); XFLR5 6.10.03 version 18 January 2024, HP Laptop with product number 2UA4280ZQ1, Colour printer, and Microsoft Office Word 2019.

1.2 Methods

1.2.1 Selection of NACA aerofoil models and geometry

The selection of NACA-suitable aerofoil models that have been proven to perform effectively in low Reynolds number conditions, typically below Re= 1×10^5. This selection was based on a thorough review of the existing literature and previous studies that identified the aerofoil models capable of stable operation under such conditions. It can be seen that data on the original aerofoil samples were sourced from the XFLR5 software. The aerofoil models were selected from the original aerofoil models that operate in low-speed aerodynamic applications.

The selection was made by choosing the original NACA aerofoils, taking into account their varying camber and thickness [11]. Similarly, the selection process further considered NACA aerofoils with low, high, and no camber to their maximum thickness positions, as shown in Table 1.

Table 1: Specifications of the NACA Aerofoil Parameters

NACA Aerofoil Specification	4415	2412	0015
Chord length (m)	0.5886	0.5886	0.5886
Wing span (m)	5.1257	5.1257	5.1257
Maximum camber of the chord (%)	4	2	0
Maximum camber position from the leading edge (%)	40	40	0
Thickness of the chord (%)	15	12	15
Maximum thickness position (%)	30	30	30

2.2.3 Design of NACA aerofoil models using Xflr5 software

The design process begins with importing the geometry of the original NACA 4415, NACA 2412, and NACA 0015 aerofoils, and the doum leaf stalk composite properties such as tensile strength of optimum 28.670 MPa, a flexural strength of 52.450 MPa, impact strength of 0.500 J/m^2, hardness of HV 59.60, single fibre pull-out test with maximum load of 8.55 N into XFLR5 software through direct foil design. The foil files for NACA profiles are selected to facilitate easy manipulation and analysis of aerofoil shapes. Users can define or import 2D aerofoil geometries, including various NACA profiles, and input essential parameters such as wingspan, chord length, thickness, maximum thickness position, number of panels, and Reynolds number to model a complete aerofoil structure. The software employs methods such as Lifting Line Theory (LLT) and Vortex Lattice Methods (VLM) to simulate the aerofoil and calculate aerodynamic coefficients, including lift (C_l), drag (C_d), and lift-to-drag ratio (L/D) at different angles of attack [13].

2.2.4 Modification and optimization of the NACA aerofoil models

Once the complete aerofoil structure was obtained, the next step involved modifying and optimizing the parameters using the XFOIL inverse design tool from XFLR5 software. The modifications included adjustments to the aerofoil's maximum thickness and the position of maximum thickness, transitioning from the original model to the new model [13]. The optimization also enhanced the lift-to-drag C_l/C_d ratio, C_l, C_d, C_p, and revealed optimal aerodynamic values at specific angles of attack through performance analysis at constant low Reynolds numbers 1×10^5. The C_l, C_d values, and meshing were further optimized using CFD simulations, which determined the moment coefficient and pressure distribution across angles of attack ranging from 1° to 15°. The shapes of the original NACA 4415, 2412, and 0015 aerofoils were modified to design a new aerofoil aimed at increasing aerodynamic efficiency using XFLR5 software. These adjustments improved lift-to-drag ratios (C_l/C_d), as well as C_l, and C_d, values, at varying angles of attack, thereby enhancing the overall aerodynamic efficiency of the NACA aerofoil [14]. Furthermore, XFLR5 provided graphical outputs, including polar plots, to visually represent the aerodynamic performance.

2.2.5 Aerodynamic performance of the NACA aerofoils and validation against experimental wind data to assess their suitability for specific applications

Based on the simulation results, the users compared different iterations against each other to evaluate improvements in aerodynamic efficiency. One of the critical steps in validating the design is comparing optimized results with experimental wind data, which ensures that the model accurately predicts real-world behaviour [15]. In the final design selection, users can select the best-performing design based on their maximum lift with minimum drag and maximum lift-to-drag ratio and stall characteristics [11]. The performance of each NACA aerofoil was given to suitability in specific applications such as drones for Unmanned Aerial Vehicles (UAVs) that improve lift and stability, wind turbine blades by designing blades that maximize efficiency at specific wind conditions and model aircraft design that enhance performance for the hobbyist or competitive model planes [13].

3. Results and Discussion

3.1 Results

These results obtained from the design, simulation, and optimization of the NACA 4415, 2412, and 0015 aerofoils for low-speed applications using XFLR software. The geometry shape of the three NACA aerofoils and aerodynamic parameters analyzed include lift coefficients, drag coefficients, and lift-to-drag ratio across various angles of attack. These results are presented and discussed comparatively. The findings demonstrate considerable agreement with the optimum values obtained from the design software and align well with the outcomes of previous studies and experimental wind data, highlighting the reliability and accuracy of the simulations.

3.2 Design of NACA Aerofoil Models Using XFLR5 Software

The design model produced from the NACA standard coordinate using XFLR5 software which includes; the aerofoil geometries, graphical representation of lift coefficient, drag coefficient, lift-to-drag ratio, moment coefficients, and simulation status of the three aerofoils NACA 4415, 2412, and 0015 are presented in Figures 1, 2, and 3 respectively.

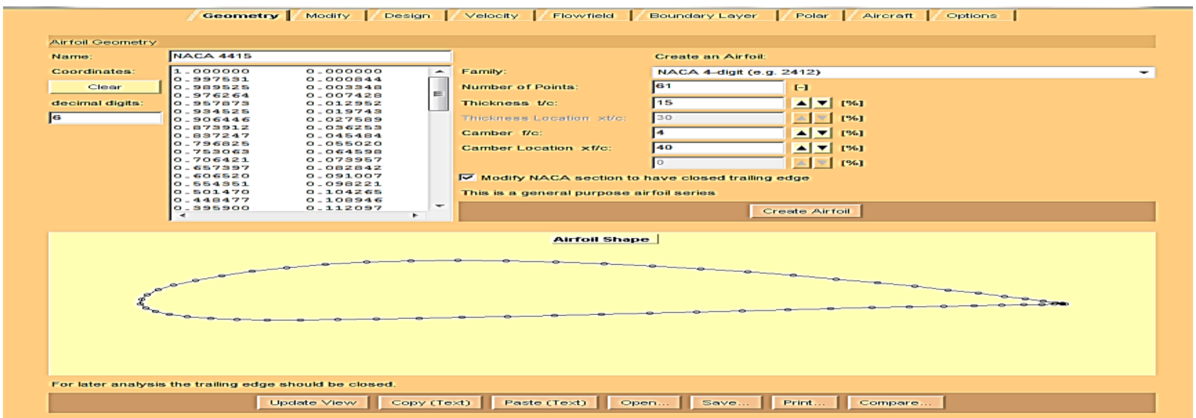

Figure 1: NACA 4415 Aerofoil Geometry

Figure 1 depicts the NACA 4415 aerofoil, an asymmetrical geometry specifically designed to enhance aerodynamic performance by optimizing lift and drag coefficients. The aerofoil's shape was produced using precise coordinates and panels, ensuring an accurate and efficient design tailored for aerodynamic applications through XFLR5 software. This particular aerofoil was selected for its high maximum camber, which is 4% of the chord length, making it highly effective in generating lift while minimizing drag. This aerofoil is characterized by its 15% thickness-to-chord ratio. The asymmetrical nature of a NACA 4415 further contributes to its ability to maintain stability and efficiency in varying flight conditions, making it a preferred choice for applications requiring a balance between lift and drag. This geometry is particularly suitable for scenarios where improved lift characteristics are essential, such as in aircraft wings and other aerodynamic structures [12].

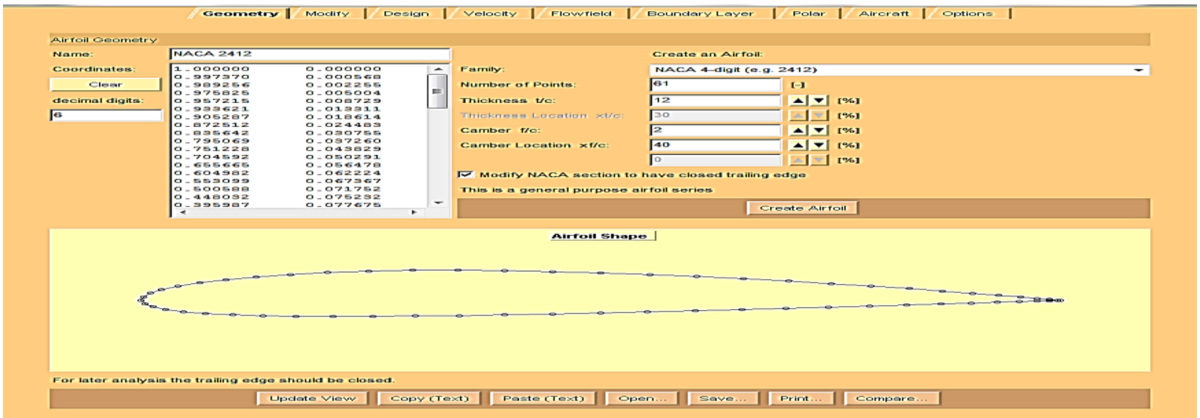

Figure 2: NACA 2412 Aerofoil Geometry

Figure 2 illustrates the NACA 2412 aerofoil, a symmetrical geometry engineered to achieve a balanced performance in terms of lift and drag coefficients. This aerofoil is characterized by its maximum camber of 2% of the chord, positioned at 40% of the chord length from the leading edge, making it suitable for a wide range of aerodynamic applications. This aerofoil is characterized by its 12% thickness-to-chord ratio. The shape of the aerofoil is precisely produced using coordinates and panels, ensuring accurate representation and performance optimization using XFLR5. The NACA 2412 is widely recognized for its ability to deliver a stable lift-to-drag ratio, making it ideal for aircraft wings and control surfaces where both efficiency and stability are critical. Its symmetrical nature ensures consistent aerodynamic behavior, providing reliable performance under varying operational conditions [12].

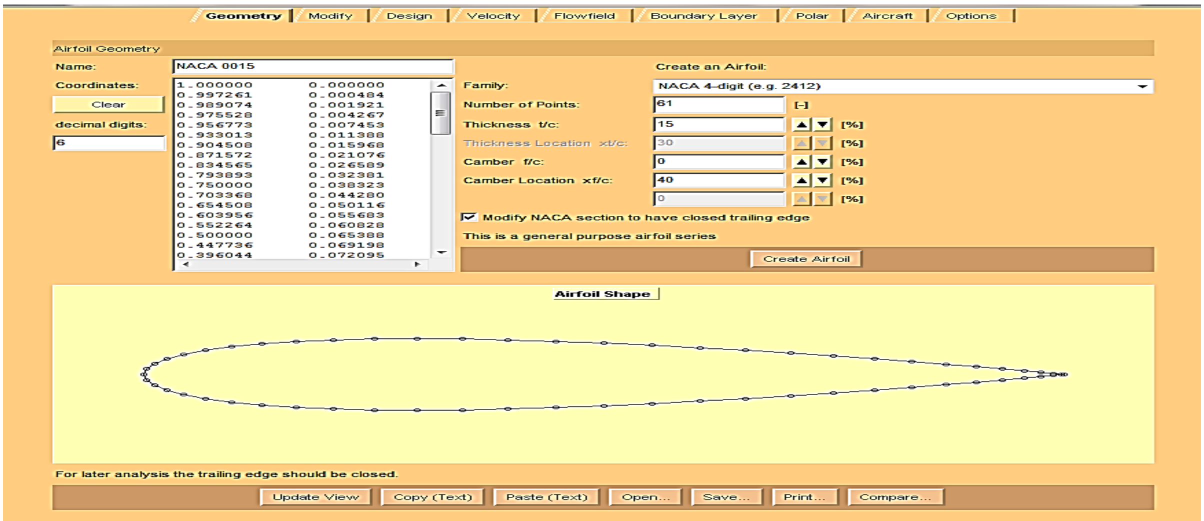

Figure 3: NACA 0015 Aerofoil Geometry

Figure 3 presents the NACA 0015 aerofoil, a symmetrical geometry with 0% camber at 0% of the chord length, designed to provide uniform aerodynamic performance across varying flight conditions. This aerofoil is characterized by its 15% thickness-to-chord ratio, symmetrically distributed about the chord line, enhancing its stability and predictable behaviour through XFLR5 software. The absence of camber ensures that the lift and drag characteristics remain consistent regardless of the angle of attack, making it highly suitable for applications requiring balanced and aerodynamic properties, such as aircraft control surfaces, wind turbine blades, and marine hydrofoils. The shape of a NACA 0015 is produced using precise coordinates and panels to ensure accurate modelling and optimal performance using XFLR5. Additionally, its robust and symmetrical design provides excellent structural integrity, making it a versatile choice for a wide range of engineering and aerodynamic applications [12].

Table 2: Simulation Results of Lift Coefficients against Drag Coefficients for the NACA 4415, 2412, and 0015 Aerofoils

Angle of attack (AoA) [α^0]	**NACA 4415**		**NACA 2412**		**NACA 0015**		**Simulation Status**
	C_l	**C_d**	**C_l**	**C_d**	**C_l**	**C_d**	**Converged/ not Converged**
0	-	-	-	-	-	-	Not converged
1	0.584	0.019	0.409	0.016	0.290	0.017	Converged
2	0.678	0.020	0.511	0.016	0.398	0.015	Converged
3	0.782	0.021	0.610	0.016	0.478	0.015	Converged
4	0.887	0.022	0.707	0.017	0.559	0.016	Converged
5	0.979	0.023	0.803	0.017	0.636	0.017	Converged
6	1.075	0.025	0.894	0.018	0.707	0.019	Converged
7	1.177	0.026	0.975	0.019	0.778	0.023	Converged
8	1.263	0.028	1.034	0.022	0.856	0.027	Converged
9	1.351	0.029	1.085	0.027	0.936	0.032	Converged
10	1.428	0.030	1.156	0.033	1.005	0.039	Converged
11	1.464	0.031	1.236	0.040	1.033	0.049	Converged
12	1.472	0.034	-	-	1.023	0.061	Converged
13	1.457	0.041	1.259	0.061	-	-	Not Converged (0015)
14	1.438	0.050	1.164	0.079	-	-	Not Converged (0015)
15	1.430	0.061	1.022	0.114	0.445	0.152	Converged

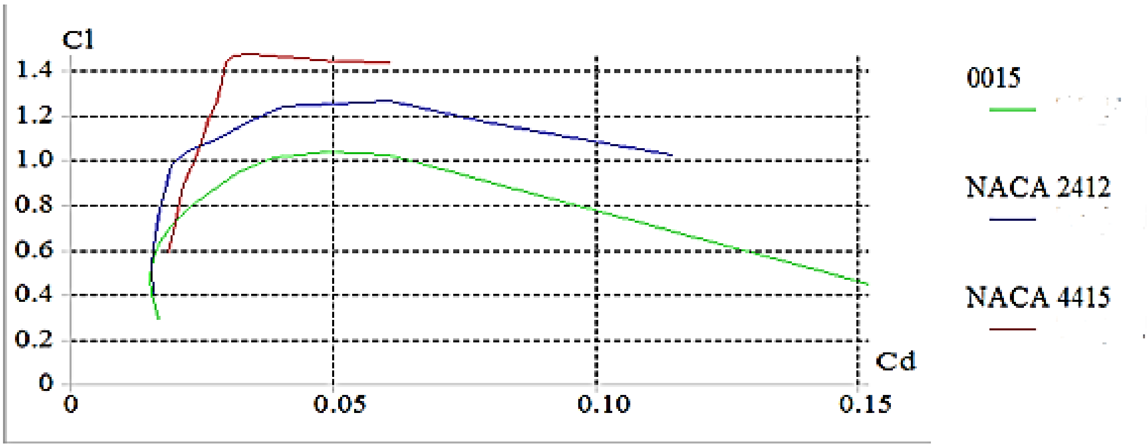

Figure 4: Graph of lift Coefficient against Drag Coefficient for the NACA 4415,2412 and 0015 Aerofoils at Re=1×10^5

Figure 4 and Table 2 present the simulation results of the NACA 4414, 2412, and 0015 aerofoils for the lift (Cl) and drag (Cd) coefficients at a low Reynolds number (Re = 1×10^5), highlighting their aerodynamic performance across various angles of attack (α). The graph in Figure 4 shows a linear region where Cl increases steadily with a relatively small increase in Cd under the same simulation conditions. For instance, at α = 10°, NACA 4415 exhibits Cl = 0.584 and Cd = 0.019, increasing to Cl = 0.979 and Cd = 0.023 at α = 5°. Similarly, NACA 2412 shows Cl = 0.409 and Cd = 0.016 at α = 10°, rising to Cl = 0.803 and Cd = 0.017 at α = 5°, while NACA 0015 follows the same trend with Cl = 0.290 and Cd = 0.017 at α = 10°, increasing to Cl = 0.636 and Cd = 0.017 at α = 5°. This indicates that as lift increases, drag remains relatively low, which is desirable for efficient flight (Abubakar *et al.*, 2020). The NACA 4415, with its high camber, achieves the highest Cl values, peaking at 1.472 with Cd = 0.034 at α = 12°, making it ideal for high-lift applications such as slow-flying aircraft, though at the cost of higher drag, which increases to Cd = 0.061 at α = 15°. NACA 2412 offers moderate lift performance, with Cl peaking at 1.259 and Cd = 0.061 at α = 13°, and a slightly higher drag, rising from 0.016 at α = 13° to 0.114 at α = 15°, making it suitable for versatile applications. In contrast, NACA 0015, with its symmetric profile, exhibits the lowest Cl values, peaking at 1.033 with Cd = 0.049 at α = 11°, followed by a significant drop in lift and aerodynamic inefficiency at higher α, with Cd increasing from 0.017 at α = 10° to 0.061 at α = 12°. The lift and drag coefficient values of the modified NACA 0015 show significant improvements compared to those reported in the literature. For instance, Krishan et *al.* [16] reported maximum coefficients of Cl = 1.023 and Cd = 0.072 at α = 11°, whereas the present results show a Cl increase of 0.96% and a Cd reduction of 31.9%. Similarly, Robiul-Islam *et al.*, [17] reported optimum values for a designed NACA 0015 as Cl = 0.197 and Cd = 0.0066 at α = 10°, while the present results indicate a significant improvement with a Cl increase of 80.9% and a Cd decrease of 25.8%, highlighting substantial aerodynamic advancements. Table 2 further presents the simulation results, showing convergence for most angles of attack except at 0° for all aerofoils, likely due to numerical instability or insufficient flow separation data. Additionally, NACA 0015 fails to converge at α = 13° and α = 14° due to excessive flow separation and vortex shedding, leading to unsteady aerodynamic forces that cause divergence in the solution. NACA 4415 and NACA 2412, while generally stable, exhibit minor convergence issues at α = 14° and α = 15°, respectively, likely due to the onset of stall, causing unsteady flow behavior. At α = 15°, the simulation converges, but NACA 0015 shows a sharp drop in Cl (0.445) and a Cd increase (0.152), confirming high drag due to stall effects, limiting its aerodynamic efficiency at high α. Figure 4 also visualizes lift and drag variations, reinforcing that NACA 4415 provides the highest lift efficiency, NACA 2412 balances lift and drag for general applications, and NACA 0015 experiences significant stall effects at high α. In conclusion, while NACA 4415 is most suitable for high-lift applications, NACA 2412 achieves a balanced performance with moderate drag, and NACA 0015, due to its symmetric profile, is more prone to stall, making it less efficient for high-lift applications.

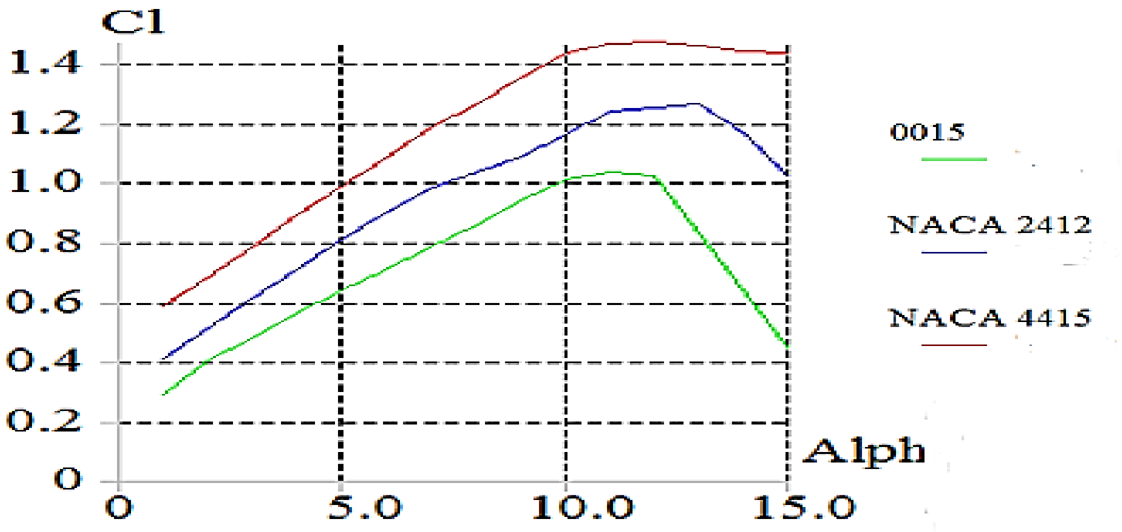

Figure 5: Graph of lift Coefficient against Angles of Attack for the NACA 4415, 2412, and 0015 Aerofoils at Re=1×10⁵

Figure 5 and Table 2 illustrate how the lift coefficient C_l varies with the angle of attack for three aerofoils NACA 4415, 2412, and 0015 alongside the simulation status at each angle of attack (α) none of the simulations converged, potentially due to challenges in resolving flow behavior at zero lift. From 1^0 to 11^0, all simulations converged, with C_l steadily increasing as AoA increased, reflecting enhanced lift generation. Among the aerofoils, NACA 4415 exhibited the highest C_l due to its pronounced camber, reaching a maximum value of 1.472 at 12^0, while the moderately cambered NACA 2412 achieved a peak C_l of 1.259 at 13^0, and the symmetric NACA 0015 attained a lower maximum C_l of 1.033 at 11^0. Conversely, the minimum C_l values for the three aerofoils occurred at, with NACA 4415 at 0.584, NACA 2412 at 0.409, and NACA 0015 at 0.290. Beyond 12^0, convergence issues arose for NACA 2412 and NACA 0015, indicating flow separation and stall conditions; NACA 2412 failed to converge after 12^0, while NACA 0015 converged again at 15^0 but with a significantly reduced C_l of 0.445 due to severe stall. NACA 4415 sustained lift generation at higher AoA, peaking at 1.472 at 12^0 before gradually declining.

Table 3: Simulation Results of Lift-to-Drag Ratio Coefficients of the NACA 4415, 2412 and 0015 at Various Angles of Attack

Angle of attack (AoA) [α^0]	**NACA 4415** C_l/C_d	**NACA 2412** C_l/C_d	**NACA 0015** C_l/C_d	**Simulation Status** Converged/ not Converged
0	-	-	-	Not converged (-)
1	31.068	25.925	17.261	Converged
2	34.444	32.884	25.835	Converged
3	38.058	38.618	31.187	Converged
4	40.973	42.815	35.051	Converged
5	41.915	46.211	36.903	Converged
6	42.990	48.842	36.405	Converged
7	44.752	50.163	34.373	Converged
8	45.295	46.655	32.088	Converged
9	46.791	39.601	29.399	Converged
10	48.340	34.763	25.927	Converged
11	47.118	30.566	21.103	Converged
12	43.003	-	16.909	Not Converged (2412)
13	35.640	20.744	-	Not Converged (0015)
14	28.499	14.740	-	Not Converged (0015)
15	23.523	8.933	2.926	Converged

The lift and drag coefficients, reported by Emmanuel *et al.,* [14] for the NACA 2408, optimum values were C_l = 1.235, and C_d = 0.046, at 8.50. Compared with the present results for the NACA 4415 and 0015, there is a significant improvement for the NACA 4415, with C_l showing a 16.1% increase, and C_d a 26%. However, for the NACA 2412, there is an improvement in the percentages for C_l and C_d values. These results demonstrate that NACA 4415 offers superior lift performance, followed by NACA 2412 and NACA 0015, and highlight the impact of aerofoil camber on aerodynamic efficiency and stall characteristics.

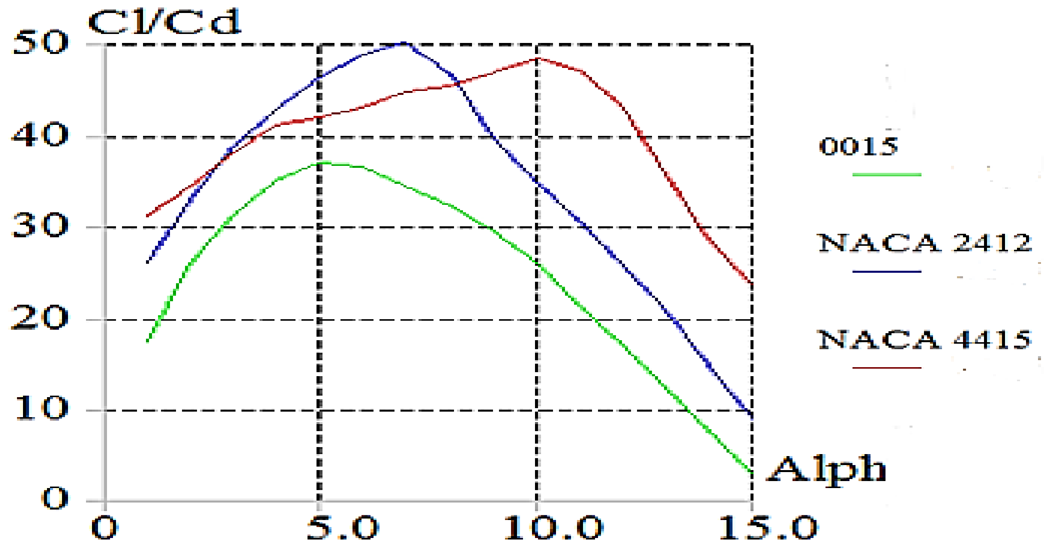

Figure 6: Graph of Lift-to-Drag Ratio Coefficients against Angles of Attack for the NACA, 4415, 2412, and 0015 Aerofoils at Re=1×10⁵

Figure 6 and Table 3 highlight the variation of the lift-to-drag ratio coefficients Cl/Cd for three aerofoils NACA 4415, 2412, and 0015 across different angles of attack (α), with Cl/Cd being a critical measure of aerodynamic efficiency. Higher Cl/Cd values are more desirable as they indicate better performance by generating maximum lift with minimal drag. The results show that Cl/Cd increases with AoA initially, peaking for each aerofoil before declining due to flow separation and pre-stall. NACA 2412 reaches the highest maximum optimum value of Cl/Cd of 50.163 at 7°, indicating optimal performance at a slightly moderate angle AoA. Based on the lift-to-drag ratio, NACA 2412 appears to be the best-modified aerofoil, followed by NACA 4415, which achieves moderate optimum values of Cl/Cd of 48.340 at 10°, demonstrating strong optimum performance over a wide AoA range. Meanwhile, NACA 0015's optimum values occurred at 36.903 at 5°, reflecting its lower efficiency due to its symmetric design. Beyond their respective peak values, Cl/Cd decreases, with NACA 4415 maintaining higher optimum values even in pre-stall conditions, dropping to 23.523 at 15°, while NACA 2412 and NACA 0015 experience steeper declines to 8.933 and 2.926 at 15°, respectively.

The lift-to-drag ratio values of the optimized NACA 6409 using XFLR5 for optimization demonstrate superior aerodynamic performance, as reported by Timothy et al. (2023), with an optimum Cl/Cd value of 28 at 11°. Compared to these results, the modified NACA 4415, 2412, and 0015 show significant improvements, with Cl/Cd values of 42% at 10°, 44% at 7°, and 24% at 5°, respectively. Similarly, Le-Quang *et al.,* [13] reported modifications of the S1010 aerofoil model, resulting in the new VAST-EPU-S1010 model, which included adjustments to the aerofoil's maximum thickness from 6.02% to 8%, its maximum thickness position from 23.42% to 19.32%, maximum camber from 0.00% to 6.4%, and maximum camber position from 0.00% to 59.56%. These modifications, along with other geometric enhancements using inversion techniques, improved the lift-to-drag Cl/Cd ratio. Performance analysis at low Reynolds numbers revealed optimal aerodynamic efficiency at an angle of attack of 3°, with an optimum Cl/Cd value of 45.5 at 15°. Compared with the present results for a modified NACA 2412, which was geometrically modified via optimization without any alteration on the geometry, having a higher Cl/Cd value of 50.163 at 7° was achieved, representing a percentage improvement of 9.3%. These results underscore that the maximum Cl/Cd values are crucial for identifying the most aerodynamically efficient operating range, with NACA 4415 being most effective across a broad AoA range, NACA 2412 excelling at moderate angles, and NACA 0015 being most suitable for lower angles.

For comparison, Krishan *et al.* [16] reported maximum coefficients of Cl/Cd = 14.208 at 11°, while the present results show notable percentage improvements; Cl/Cd improved by 61.49%. Similarly, Robiul-Islam *et al.,* [17] reported optimum values for a designed NACA 0015 of Cl/Cd = 6.45 at 8°. Compared to the present results, there is a significant percentage improvement; Cl/Cd improved by 82.5%. These findings highlight the substantial advancements achieved in the modified NACA 0015 compared to previously reported values in the literature.

3.3 Wing and Plane Design with Mesh Generation of the Optimized Shape and Structure of NACA 4415, NACA 2412, and NACA 0015 Aerofoils

The NACA 4415, 2412, and 0015 aerofoils parameters with plane design structure produced, including the mesh generation elements are presented in Table 4, Figure 7, Figure 8, and Figure 9 respectively.

Table 4: Wing and Plane Design Parameters of the NACA 4415, 2412 and 0015 Optimized Aerofoil with Mesh Generation Elements

Aerofoil Parameters	**ModifiedNACA 4415**	**Modified NACA 2412**	**Modified NACA 0015**
Wing span (m)	5.1257	5.1257	5.1257
Wing area (m^2)	1.506	1.506 0.5886	1.506
Chord length (m)	0.5886		0.5886
Plane mass (kg)	0.000	0.000	0.000
Wing load (kg/m^2)	0.000	0.000	0.000
Root chord (m)	0.294	0.294	0.294
Aspect Ratio	17.429	17.429	17.429
Tip Twist (°)	0.000	0.000	0.000
Root tip-swept (%)	0.000	0.000	0.000
Mesh elements	484	450	450

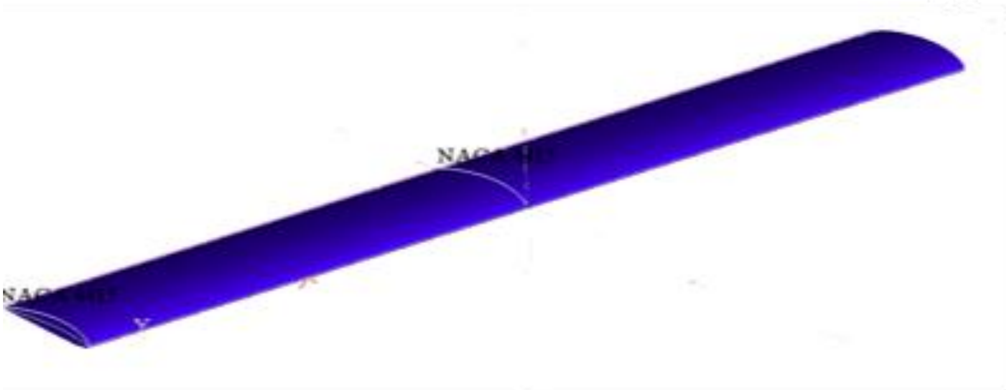

Figure 7: Wing and Plane Design with Mesh Generation of the Optimized shape and Structure of NACA 4415 Aerofoil

Figure 8: Wing and Plane Design with Mesh Generation of the Optimized Shape and Structure of NACA 2412 Aerofoil

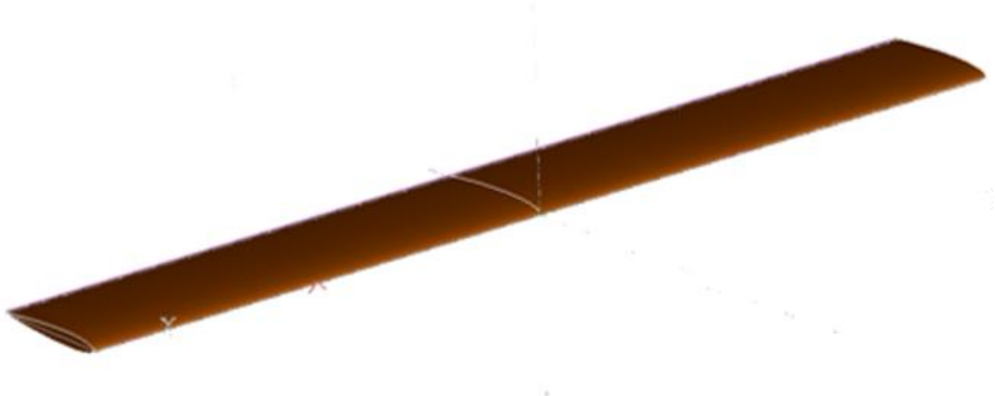

Figure 9: Wing and Plane Design with Mesh Generation of the Optimized Shape and Structure of NACA 0015 Aerofoil

From Table 4 and Figures 7, 8, and 9 respectively, provide a detailed comparison of three optimized aerofoil profiles modified NACA 4415, modified, 2412, and modified 0015 focusing on their geometric parameters and mesh generation. The wing span 5.1257 m, wing area 1.506 m², root chord 0.294 m, aspect ratio 17.429, tip twist 0.000°, and root tip-swept 0.000% are identical for all three designs, ensuring consistency for comparative analysis. However, the mesh element count varies, with modified NACA 4415 having the highest 484, allowing for finer computational resolution, while modified NACA 2412 and NACA 0015 have 450 mesh elements each. Figures 15, 16, and 17 visually represent the aerofoils' optimized shapes and mesh distributions, emphasizing their unique aerodynamic characteristics. The modified NACA 4415, with its higher camber and mesh density, is optimized for high-lift applications, capturing detailed flow phenomena more effectively, the mesh type is unstructured triangular mesh size of 484 elements with moderate growth rate to maintain a smooth transition between the elements, and the element size gradually increased element size from the aerofoil surface to the far-field. In contrast, the modified NACA 2412, with moderate camber, offers an unstructured triangular mesh with mesh size of 450 elements, it is similar to NACA 4415, with a gradual increase in element size from the aerofoil surface to the far-failed, and the growth rate is moderate. It also offers a balance between lift and drag, making it suitable for general aviation, while the symmetrical modified NACA 0015 offers an unstructured triangular mesh with mesh size of 450 elements, it is similar to a NACA 2412 aerofoil with a gradual increase in element size from the aerofoil surface to the far-failed, and the growth rate is moderate. This ensures predictable performance across various angles of attack, ideal for aerobatic planes or control surfaces. This comprehensive comparison highlights the distinct roles and computational precision of each aerofoil, with the modified NACA 4415 leading in detailed aerodynamic analysis. The finer mesh generation in modified NACA 4415 ensures superior accuracy in Computational Fluid Dynamics (CFD) analysis, based on the mesh generation parameters with highest number of elements, making it the best option for detailed aerodynamic performance studies, followed by NACA 2412 and 0015 aerofoils. This comparison underscores the distinct roles of each aerofoil, optimized for specific applications, with modified NACA 4415 leading in computational precision and aerodynamic potential.

3.4 Aerodynamic Performance of NACA 4415, 2412 and 0015Aerofoils and Validation Against Experimental Data to Assess Their Suitability for Specific Applications

The aerodynamic performance and validation against experimental data to assess their suitability for specific applications of the NACA 4415, 2412, and 0015 aerofoils for coefficients of lift, drag, and the ratio of lift-to-drag against angle with percentage improvement are presented in Tables 5, 6 and 7 respectively.

Table 5: Results of Optimization and Validation against Experimental Data to Assess their Suitability for Specific Applications NACA 4415, 2412 and 0015 for Lift Coefficients

parameters	Modified NACA 4415	Experimental NACA 4415	Modified NACA 2412	Experimental NACA 2412	Modified NACA 0015	Experimental NACA 0015
Cl	1.472	1.357	1.259	1.214	1.033	0.89
AoA	12	15	13	15	11	15
% Improvement	8.47		3.71		16.07	

Table 5 presents the comparison between the modified and experimental NACA aerofoils (4415, 2412, and 0015) at different angles of attack, demonstrating significant performance enhancements across all designs, particularly in terms of lift coefficient C_l and aerodynamic efficiency. For the high-camber NACA 4415, the modified version achieves an 8.47% improvement in C_l (1.472 vs. 1.357) at the different angle of attack (AoA) of 12° and 15° respectively, solidifying its role in high-lift applications for general aviation that is suitable for small, single-engine planes, and model aircraft enhanced lift is critical [11]. Modified NACA 2412, characterized by moderate camber, shows a smaller C_l improvement of 3.71% (1.259 vs. 1.214) but accomplishes this at a reduced AoA of 13° instead of 15°, highlighting improved aerodynamic efficiency while maintaining its versatility for generalpurpose applications slow-speed aircraft such as light aircraft and sailplanes, wind tunnel testing, aerodynamic research or flaps for where a balance between lift and drag is necessary. On the other hand, the symmetrical NACA 0015 exhibits the most striking enhancement, with a 16.07% increase in C_l (1.033 vs. 0.89) and a significant reduction in AoA from 15° to 11°, broadening its usability in dynamic applications such as aerobatic planes, helicopter rotor, compressor and wind turbine blades, missile and rocket, hydrofoil and marine applications, where lift symmetry and efficiency are essential [11]. Overall, the modifications to these aerofoils lead to higher lift coefficients and enhanced aerodynamic performance, with NACA 0015 benefiting the most from the adjustments, reflecting its potential for diverse applications, followed by NACA 4415, which remains an exceptional high-lift performer, and NACA 2412, which retains its balanced and versatile profile. These results demonstrate how targeted modifications can tailor aerofoil designs to meet specific operational needs while improving their overall aerodynamic efficiency and performance [13].

Table 6: Results of Optimization and Validation against Experimental Data to Assess their Suitability for Specific Applications NACA 4415, 2412 and 0015 for Drag Coefficients

parameters	Modified NACA 4415	Experimental NACA 4415	Modified NACA 2412	Experimental NACA 2412	Modified NACA 0015	Experimental NACA 0015
C_d	0.034	0.071	0.061	0.116	0.049	0.093
AoA	12	15	13	13	11	15
% Improvement	52.11		47.41		47.31	

Table 6 presents the optimization validation of the three NACA aerofoils (4415, 2412, and 0015) revealing varying degrees of improvement in aerodynamic performance, particularly in drag reduction C_d, highlighting their suitability for specific applications. For NACA 4415, the optimised drag coefficient C_d of 0.034 represents a 52.11% improvement compared to the experimental value of 0.071, showcasing its un-balanced performance at a high angle of attack of 12^0 and 15° respectively, making it ideal for applications requiring strong lift, such as fixed-wing aircraft. In contrast, NACA 2412 demonstrated a minimal improvement of 47.41%, with the drag coefficient C_d significantly decreasing from 0.116 to 0.061 at both AoA 13° indicating that this aerofoil is already far-optimal and remains a reliable choice for applications needing a balanced lift-to-drag ratio at moderate angles of attack. The most significant improvement was observed in NACA 0015, where the optimized drag coefficient C_d of 0.049 at moderate angle of attack 11° which marked a substantial 47.31% reduction from the experimental value of 0.093 at 15^0, emphasizing its potential for low-drag, high-speed applications, particularly at moderate angles of attack 11°, such as in helicopter blades or rudders [11]. Overall, NACA 4415 offers the greatest aerodynamic gains, balances lift and drag effectively at high angles, and NACA 2412 remains well-suited for general aerodynamic needs. NACA 0015, emphasizing its potential for low-drag, high-speed applications [13].

Table 7: Results of Optimization and Validation against Experimental Data to Assess their Suitability for Specific Applications NACA 4415, 2412 and 0015 for Lift to Drag Ratio

parameters	Modified NACA 4415	Experimental NACA 4415	Modified NACA 2412	Experimental NACA 2412	Modified NACA 0015	Experimental NACA 0015
C_l/C_d	48.34	20.5	50.163	22.5	36.903	21.2
AoA	10	15	7	15	5	15
% Improvement	135.8		122.93		74.06	

Table 7 presents a comparison of the lift-to-drag ratio C_l/C_d between the modified and experimental NACA aerofoils (4415, 2412, and 0015), revealing significant improvements in aerodynamic efficiency across all designs. The modified NACA 4415 achieves the optimum value of lift-to-drag ratio of 48.34 at 10^0 marking a 135.8% improvement over the experimental value of 20.5 at an angle of attack (AoA) of 15° indicating a much more efficient aerodynamic performance, particularly in reducing drag while maintaining high lift making it ideal for applications requiring strong lift, such as fixed-wing aircraft. Similarly, the modified NACA 2412 shows a 122.93% improvement, with the lift-to-drag ratio rising to the optimum value of 50.163 at 7^0 from the experimental 22.5 at 15° AoA, highlighting its enhanced performance in applications requiring a balance between lift and drag, such as in commercial or general aviation [11]. The modified NACA 0015 exhibits a **74**.06% increase in the lift-to-drag ratio, reaching an optimum value of 36.903 at 5^0, compared to the experimental 21.2 at 1**5°** AoA, underscoring its greater aerodynamic efficiency, particularly in low-drag, high-speed applications like helicopter blades or rudders. Overall, the modifications in all three NACA aerofoils result in significantly improved aerodynamic efficiency, with the NACA 2412 showing the highest improvement, followed by NACA 4415 and NACA 0015**,** demonstrating the substantial impact of optimization on increasing lift and reducing drag, thereby enhancing the suitability of these airfoils for various aerodynamic applications where maximizing efficiency is crucial [13].

4. Conclusion

The design, simulation, and optimization of NACA 0015, 2412, and 4415 aerofoils were successfully conducted using XFLR5 software, focusing on enhancing aerodynamic efficiency. The modified NACA 0015 underwent adjustments, reducing its thickness from 15% to 13%, shifting its maximum camber position to 29%, and refining its aerodynamic performance for drag coefficient and lift-to-drag ratio, making it ideal for symmetric aerofoil and high-speed applications. The geometric designs of NACA 2412 and 4415 remained unchanged, but optimization significantly improved their lift, drag, and lift-to-drag ratio without altering their original geometry. NACA 4415, with its higher camber, demonstrated the highest lift coefficient (Cl), peaking at 1.472 with a drag coefficient (Cd) of 0.034 at $\alpha = 12°$, indicating excellent lift generation for high-lift applications. NACA 2412 offered moderate lift performance, with Cl peaking at 1.259 and Cd at 0.061 at $\alpha = 13°$, while NACA 0015, being symmetric, exhibited the lowest Cl values, peaking at 1.033 with Cd = 0.049 at $\alpha = 11°$, reflecting its reduced aerodynamic efficiency at higher α. The lift-to-drag ratio (Cl/Cd) increased with AoA initially, peaking before declining due to flow separation and pre-stall effects. NACA 2412 achieved the highest Cl/Cd of 50.163 at 7°, making it the best-modified aerofoil for balanced applications, followed by NACA 4415, which reached 48.340 at 10°, excelling across a wide AoA range. NACA 0015 had its highest Cl/Cd of 36.903 at 5°, indicating lower efficiency due to its symmetric design. Beyond their peak values, Cl/Cd declined, with NACA 4415 maintaining higher efficiency in pre-stall conditions, dropping to 23.523 at 15°, while NACA 2412 and NACA 0015 dropped steeply to 8.933 and 2.926, respectively. The aerodynamic improvements in the modified aerofoils were substantial, with NACA 4415 showing an 8.47% increase in Cl and a 52.11% Cd reduction, making it ideal for high-lift applications such as general aviation. NACA 2412 demonstrated a 3.71% Cl increase and a 47.41% Cd reduction, optimizing it for versatile applications in light aircraft, sailplanes, and aerodynamic research. NACA 0015 exhibited a 16.07% Cl increase, a 47.31% Cd reduction, and an improved Cl/Cd ratio by 74.06%, making it well-suited for high-speed, low-drag applications such as helicopter rotors, wind turbine blades, and marine technologies. The study successfully optimized these aerofoils using CFD analysis, enhancing their aerodynamic efficiency, with NACA 4415 excelling in high-lift applications, NACA 2412 offering versatility, and NACA 0015 optimized for high-speed and low-drag uses.

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