Computational Analysis of the Aerodynamic Performance of NACA 4412 and NACA 23012 Airfoils

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Abstract - *The primary aim of this research paper is to perform two-dimensional computational fluid dynamics (CFD) analysis on the NACA 4412 and NACA 23012 airfoils. The paper also explores the historical context of the NACA series, airfoil nomenclatures and applications, as well as the respective advantages and limitations. To create two-dimensional models of the airfoils, geometry data sourced from the National Advisory Committee for Aeronautics was utilized, and these models were subsequently designed and meshed in ANSYS. The simulations were carried out using ANSYS FLUENT, employing a steady-state, viscous flow approach and the Spalart-Allmaras turbulence model in Ansys Fluent 2019. The objective is to calculate and visualize various parameters such as the lift coefficient, drag coefficient, pressure distribution, and velocity changes across different angles of attack while keeping all other conditions constant. Additionally, the analysis includes determining the stall angle. The results show that the lift coefficient increases with the angle of attack up to a certain point,but thereafter falls due to flow separation. Similarly, the drag coefficient for both airfoils increases with angle of attack, but the rate of increase is much faster past a certain angle of attack due to flow separation. Additionally, it shows that the lift coefficient is consistently higher for NACA 4412 when compared to NACA 23012 at each angle of attack. Furthermore, the critical angle of attack for NACA 23012 was observed to be 18°, while the flow separation for NACA 4412 happened at 17°.*

Key Words: Airfoil, Angle of Attack, NACA Series, Spalart-Allmaras, Lift coefficient, Drag coefficient, Stall angle, flow separation

1. INTRODUCTION

An airfoil is the cross-sectional shape of a wing that is oriented vertically to the direction of airflow. It is also referred to as a streamlined body that plays a crucial role in generating more lift than drag. The generation of lift force by an airfoil is attributed to the pressure difference between the upper and lower surfaces of the airfoil. There are two types of airfoils which are symmetrical and non-symmetrical. A symmetrical airfoil is one in which the upper and lower surfaces are identical, while a non-symmetrical airfoil, also known as a cambered airfoil, has distinct upper and lower surfaces. In the case of an asymmetrical airfoil, the camber line is positioned either above or below the chord line, whereas in a symmetrical airfoil, the camber line coincides with the chord line. Gravity is counteracted by lift, which is generated as air flows over and under the airfoil, supporting the aircraft in flight. Efficient airfoils are capable of producing less drag and greater lift, thereby enhancing fuel efficiency and the speed of the aircraft. Aircraft safety relies heavily on the airfoil's ability to maintain favorable stall characteristics, ensuring that the aircraft can generate adequate lift at varying angles of attack. Additionally, the lift-to-drag ratio in aircraft is of paramount importance as it directly influences the aircraft's range and endurance.The composition of the airfoil significantly impacts the controllability and stability of the aircraft since control surfaces like ailerons, elevators, and rudders depend on its characteristics. Different airfoil profiles can also alter the speed range of an aircraft, affecting its performance, with some aircraft designed for high-speed flight and others optimized for slower speeds.Furthermore, the choice of airfoil design can influence the overall layout and weight of the aircraft, subsequently impacting fuel efficiency. Designers and engineers carefully select airfoils based on the specific requirements and needs of the aircraft in question.

In the field of aviation, airfoil design plays a crucial and fundamental role, particularly in the creation of wings that generate lift for aircraft. The primary objective is to optimize the lift-drag ratio by reducing drag and increasing lift, thereby enhancing the overall performance, endurance, and range of the aircraft. The flow of air over and under the wing is carefully engineered to create the necessary lift, and the specific airfoil design used greatly influences the amount of lift generated. Different aircraft types call for varying airfoil configurations. For instance, symmetric airfoils are typically employed in commercial aircraft, whereas cambered airfoils are favored in high-speed fighter jets that require exceptional lift. Furthermore, airfoils are tailored for different Mach number ranges, with supersonic aircraft utilizing cambered airfoils and subsonic aircraft opting for symmetrical airfoils. The distribution of forces across the wing is meticulously designed to ensure structural integrity and load-bearing capability during flight.

With the rapid development of technology and computing, Computational Fluid Dynamics (CFD) simulations are now widely employed to analyze the airflow characteristics around airfoils, aiming to enhance their performance. This technology has found extensive applications in aerospace design, the automotive industry, and various other engineering domains. The utilization of computational simulations offers several advantages, including cost reduction in design, shortened computational cycles, and an overall improvement in design quality. Nonetheless, CFD has its limitations, primarily due to the current constraints in computer performance technology. This can lead to inaccuracies in CFD simulations when compared to real-world scenarios. In airfoil design, relying solely on CFD technology may not suffice. Instead, an array of effective methods is often necessary to modify the base model to align the aerodynamic performance calculated by CFD with the desired objectives until the anticipated results are achieved. As a result, airfoils are subjected to wind tunnel testing to validate their aerodynamic characteristics, ensuring their productivity.

1.1 Background

The National Advisory Committee for Aeronautics, commonly known as NACA, was established in 1915 as a U.S. federal agency. It played a pivotal role in the development of aviation technology and made significant contributions to the field. NACA's achievements included the enhancement of high-speed wind tunnels, the design and structural shaping of aircraft, and advancements in aerodynamics. One of the notable outcomes of NACA's research was the creation of the P-51 Mustang, an iconic aircraft used during World War II. NACA also developed a structured series of airfoil shapes known as the "NACA airfoil series." These airfoil profiles were meticulously designed using mathematical curves to streamline aerodynamic performance. Technical reports were published, providing engineers with valuable information on the aerodynamic characteristics of various airfoil shapes, aiding them in the design of diverse aircraft. NACA's practice of openly sharing their research findings greatly benefited engineers and technicians, leading to substantial improvements in aircraft performance. As aviation technology continued to advance, with the emergence of transonic and supersonic flight, NACA expanded its research to create airfoils specifically tailored to these flight conditions. This was instrumental in refining and specifying aircraft capable of flying beyond the speed of sound.

Scientists and aviation pioneers diligently studied and analyzed the aerodynamic behaviors, lift, drag, and stall characteristics of various airfoil shapes and designs. They pioneered experimental techniques for airfoil testing within high-speed wind tunnels and developed instrumentation to accurately calculate and measure aerodynamic forces. The data and knowledge accumulated by NACA continue to serve as the foundation for the aviation, aerospace, and aeronautical industries, supporting the development of safer, highly efficient, cost-effective, and high-performance aircraft.

1.2 Aircraft Nomenclature

Airfoil nomenclature is the system of naming and classifying the various characteristics and feature of an airfoil, which is the cross-sectional shape of aircraft wing. This specialized terminology helps engineers, designers, and researcher understand and communicate key properties of an airfoil. Key components of airfoil nomenclature comprise:

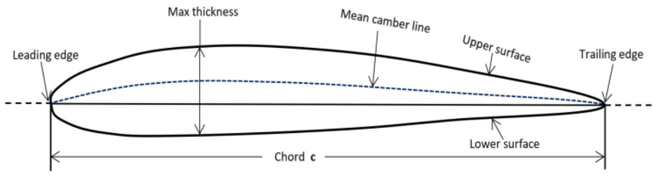


Fig-1: Aircraft Nomenclature

Leading Edge: The leading edge of an airfoil is the front edge, where the airflow first interacts with the wing.
Trailing Edge: The trailing edge of an airfoil is the point at which the airflow splits from the wing.
Chord line: Straight line acting between leading edge and trailing edge of an airfoil.
Camber line: The camber line represents the curvature and is commonly described as the distance between the chord line and the upper or lower surface of the airfoil at various points along the chord.
Maximum Chamber: Maximum distance between chord line and camber line.
Thickness: Measurement of distance of it's upper surface to lower surface and defines about the shape of an airfoil.
Stall: Critical aerodynamic condition at which the lift suddenly decreases and drag increases because of angle of attack.
Angle of attack: Angle between relative wind and chord line. Increase in angle of attack results augmenting lift of the aircraft.
Lift: Upward force acting on aircraft which is opposite to it's weight and produced because of pressure difference between upper and lower surface of airfoil.
Drag: Aerodynamic force acting backward or opposite to aircraft's motion in air.

2. NACA SERIES

The NACA airfoil series is a historically significant classification system that defines the shape and performance characteristics of airfoils used in aviation. This series, developed by NACA, which was prior to NASA, uses numerical codes to express key airfoil parameters such as camber and thickness. The NACA series gave engineers and designers a systematic method to choose

airfoils for varied purposes by describing their aerodynamic properties. Each numerical designation in the NACA series provides information about the camber, thickness, and other essential dimensions of the airfoil. This series is still used by researchers and engineers when building and studying airfoils because it lays the groundwork for understanding and maximizing the performance of aircraft wings and other aerodynamic surfaces.
In our research project, we have selected airfoils from both the NACA-4 and NACA-5 digit series and conducted a comprehensive aerodynamic performance analysis through computational simulations. Specifically, the airfoils chosen for this project are the NACA 4412 and NACA 23012, which are recognized as widely used airfoil profiles. Further detailed information regarding these airfoils is provided below:

2.1 NACA 4412

The NACA airfoil 4412 belongs to the four-digit NACA series and was developed in the early 20th century. This airfoil is symmetrical, with its camber line positioned either above or below the chord line. It offers a wealth of information, calculations, and measurements regarding the airfoil's design characteristics. The moderately cambered profile, with variations in the upper and lower surfaces, is commonly used in aircraft wings to provide stability in terms of lift and drag, making it suitable for a wide range of applications. Due to its flat bottom surface, it effectively prevents the negative ground effect caused by the generation of venturi flow. This airfoil contributes to stable aircraft performance when the angle of attack varies, addressing essential aerodynamic requirements. For achieving balanced lift, the airfoil should ideally be at a zero angle of attack, making it well-suited for specific aircraft configurations. The first digit, "4," indicates the maximum chamber location at 40% of the chord length from the leading edge, meaning the maximum camber is 0.2 times the chord length. The second digit denotes the position of the maximum camber from the leading edge, with "4" indicating it is at 0.4 times the chord length from the leading edge. The last two digits represent the maximum thickness of the airfoil section as a percentage of the chord length, with "12" indicating that the maximum thickness is 12% of the chord length behind the leading edge.

2.1.1 Advantage of NACA 4412 airfoil

The NACA 4412 airfoil stands as a remarkable feat of aerodynamic engineering, offering a suite of invaluable advantages that have a significant impact on aircraft performance, safety, and efficiency. These advantages are not only technically sound but also deliver practical benefits to pilots, engineers, and the aerospace industry as a whole.

- Balanced Performance: This airfoil provides a well-rounded performance across various flight conditions, effectively managing lift and drag even as the angle of attack varies.
- Predictable Stall Behavior: The NACA 4412 airfoil exhibits mild and predictable stall behavior, instilling confidence in pilots and ensuring safe and stable flights, thereby enhancing aircraft reliability.
- Airspeed Control: The airfoil's shape allows for effective control of airspeed, as it enables the conservation of lift during smooth initial climbs and landings. This feature is particularly valuable for aircraft operating on shorter runways and in training scenarios.
- Ease of Manufacture: The airfoil's minimal contour complexity simplifies the manufacturing process, reducing production costs and promoting cost-efficiency.
- High Lift Coefficients: Thanks to its greater thickness compared to thinner airfoils, the NACA 4412 airfoil exhibits high lift coefficients.
- Remarkable Aerodynamic Efficiency: The NACA 4412 airfoil's overall aerodynamic efficiency is remarkable, resulting in reduced fuel consumption.

2.1.2 Disadvantage of NACA 4412 airfoil

While the NACA 4412 airfoil offers several advantageous features, it's essential to acknowledge its limitations to make informed decisions regarding its use in aircraft design. Here are the key disadvantages

- Increased Drag at Lower Speeds: Bulkier airfoils like the NACA 4412 can lead to heightened drag at lower speeds, impacting overall efficiency and performance.
- Suboptimal for Glider Operations: The NACA 4412 may not be the best choice for glider operations, where maximizing lift and minimizing drag are paramount.
- Degraded Performance at High Angles of Attack: At elevated angles of attack, the airfoil's streamlined features can deteriorate, resulting in reduced aerodynamic performance and stall behavior.
- Limited Applicability for Specialized Aircraft: In comparison to modern airfoil designs, the NACA 4412 may not suit specialized aircraft with specific performance requirements due to its fixed geometry.

2.1.3 Application of NACA 4412 airfoil

The NACA airfoil 4412 is indeed a versatile and widely used airfoil profile, as demonstrated by its applications in various aircraft and systems, including:

- Sports Planes
- AAI-AA2 Mamba Aircraft
- Aeronca Chief Series
- Aeronca 65-TAC Defender
- General Aviation Trainers

● Small Wind Turbines

● Prototyping and Conceptual Design

2.2 NACA 23012

The NACA 23012 airfoil is a symmetrical airfoil with a uniform camber line and chord profile. It was developed in the year 1935 by NACA scholar Eastman-Jacobs in the United States. This airfoil is considered one of the most widely used airfoils in aviation due to its ability to provide high lift, low drag, and mild pitching moments, all while maintaining laminar flow on its lower surface. The symmetric design, with identical upper and lower surfaces, offers advantages in crafting well-balanced aircraft wings, particularly when lift needs to be maintained at a zero angle of attack.

The NACA 23012 airfoil's unique nomenclature reveals its key parameters. The "2" in its designation signifies a pattern lift coefficient of 0.3 when the tenths digit is multiplied by 3/2. The maximum chamber location in the airfoil is indicated by the split of the next two digits by 2, resulting in "30" which translates to 15% of the chord length. The final two numerals represent the maximum thickness as a fraction of the chord, with "12" indicating that the maximum thickness is 12% of the chord length. In this way, the initial symbol conveys aerodynamic characteristics, while the last four digits provide insights into the airfoil's geometric properties.

2.2.1 Advantage of NACA 23012 airfoil

The NACA 23012 airfoil has several significant features, all of which contribute to its versatility and usefulness for a wide range of aircraft and high-performance applications. In addition to those mentioned in the provided text, here are additional advantages:

● Low Drag for High-Speed: The NACA 23012 airfoil excels in high-speed applications, such as racing vehicles and fast aircraft, thanks to its low drag design.
● Stable Handling: It offers stable and predictable handling at modest angles of attack, making it ideal for a wide range of aircraft types.
● Aerobatic Performance: The airfoil's balanced lift characteristics enhance aerodynamics performance, allowing mirrored lift at different angles of attack.
● Versatile Across Aircraft: Its flexibility suits various aircraft, from training planes to Unmanned Aerial Vehicles (UAVs).
● Cost-Effective and User-Friendly: Its simple design and construction make it cost-effective and user-friendly, appealing to amateur builders and projects with limited resources.
● Precise Aerodynamic Assessment: Wind tunnel testing allows for precise assessment of its performance under different conditions, ensuring optimized design.

2.2.2 Disadvantage of NACA 23012 airfoil

The NACA 23012 airfoil, despite its advantages, is not without limitations. These disadvantages must be considered in aircraft design and selection:

● Limited Lift at Low Angles: The NACA 23012 airfoil cannot produce as much lift as cambered airfoils at lower angles of attack, affecting takeoff and landing performance.
● Inadequate at Low Speeds: It under performs at lower speeds, making it less suitable for aircraft operating in small flight regions or with short takeoff requirements.
● Reduced Maneuverability: The airfoil's shape limits maneuverability, potentially impacting aircraft control in specific flight scenarios.
● Incompatibility with Specialized Uses: It may not meet the requirements of specialized applications, particularly those necessitating high-speed performance.
● Increased Drag at High Angles: High angles of attack can lead to increased drag, reducing overall aerodynamic efficiency and performance.
● Fuel Inefficiency: Aircraft using this airfoil may experience fuel inefficiency, necessitating careful design and optimization.
● Complex Flow Characteristics: Understanding the airfoil's flow characteristics can be challenging, requiring advanced engineering techniques for analysis.

2.2.3 Application of NACA 23012 airfoil

The NACA 23012 airfoil has found applications in various aircraft types, thanks to its aerodynamic characteristics. These applications include:

● General aviation aircraft

● Light sport aircraft

● Unmanned aerial vehicle

● Radio – Controlled model aircraft

● Aerobatic aircraft

● Homebuilt aircraft

● Recreations aircraft

● Initial training aircraft

The NACA 23012 airfoil is a versatile choice for various aircraft, offering a balanced combination of lift and drag characteristics. This airfoil design has found successful applications in a range of aircraft models, including:

● Cessna 150

● Cessna 152

● Piper PA-38 Tomahawk

● Helio 295 Super Courier (U-10)

3. MATHEMATICAL FORMULATION

The most important factors in this research study are lift and drag. Lift coefficient represents a dimensionless quantity measure that relates the lift force to the wing's area and dynamic pressure. The drag coefficient is also a dimensionless unit that is used to quantify the resistance an object encounters when subjected to aerodynamic forces. Numerous numerical analyses have been conducted to explore lift and drag characteristics of airfoils under various conditions. In this research, the airfoil's aerodynamic performance is gauged using the lift and drag coefficients, which are defined as follows.

$$C_L = \frac{l}{0.5 \times \rho \times V^2 \times A}$$

$$C_D = \frac{l}{0.5 \times \rho \times V^2 \times A}$$

Where C_L is the lift coefficient and C_D is the drag coefficient, L is the lift, D is the drag, ρ is the density of air, V is free-stream air velocity, and A is the area of the airfoil.

The simulations were carried out using ANSYS FLUENT. These simulations were conducted at fixed Reynolds number equal to 3 × 105 , to show the effect at the transition region. Air was assumed as working medium with a constant density 1.225 kg/m3. In this paper a steady-state, viscous flow approach and the Spalart-Allmaras turbulence model are used to predict the effects of turbulence in flow over the airfoil.

The Spalart-Allmaras model was designed specifically for aerospace applications involving wall-bounded flows and has been shown to give good results for boundary layers subjected to adverse pressure gradients. The continuity equation as presented by Spalart-Allmaras is given by,

$$\frac{D\tilde{v}}{Dt} = C_{b1}(1 - f_{t2})\tilde{S}\tilde{v} + \frac{1}{\sigma}[\nabla.(v + \tilde{v})\nabla\tilde{v} + C_{b2}(\nabla\tilde{v})^2] - \left(C_{w1}f_w - \frac{C_{b1}}{k^2}f_{t2} \right)(\tilde{v}/_d)^2 + f_{t1}\Delta U^2$$

Where,

$$\tilde{S} = S + \frac{\tilde{v}}{k^2d^2}\left[1 - \frac{\tilde{v}}{v}\left(1 + \frac{(\tilde{v}/_v)^4}{(\tilde{v}/_v)^3 + C_{v1}^3}\right)^{-1} \right]$$

$$f_w = \frac{\tilde{v}}{\tilde{S}k^2d^2}\left[1 + C_{w2}\left(\left(\frac{\tilde{v}}{\tilde{S}k^2d^2}\right)^5 - 1\right)\right](1 + C_{w3}^6)^{\frac{1}{6}}\left\{\left[1 + C_{w2}\left(\left(\frac{\tilde{v}}{\tilde{S}k^2d^2}\right)^5 - 1\right]^6 + C_{w3}^6\right\}^{\frac{-1}{6}}$$

$$f_{t1} = C_{t1}g_t exp\left[-C_{t2}\frac{\omega_t^2}{\Delta U^2}(d^2 + g_t^2d_t^2)\right]$$

$$f_{t2} = C_{t3}exp\left[-C_{t4}\left(\frac{\tilde{v}}{v}\right)^2\right]$$

The constants defined below that are used in the Spalart-Allmaras turbulence model are:
C_{b2} = 0.622, k = 0.4187, C_{w1} = 3.239, C_{w2} = 0.3, C_{v1} = 7.1, C_{t1} = 1, C_{t2} = 2, C_{t3} = 1.2, C_{t4} = 0.5

$$g_t = min\left(0.1, {}^{\Delta U}/_{\omega_t \Delta x_t}\right)$$

4. COMPUTATIONAL METHOD

4.1 Geometry and Mesh Generation

Two-dimensional airfoil shapes were generated, and the meshing process was completed using Ansys. A computational domain which was used in this simulation was shown in fig 2. Both the velocity inlet and pressure outlet are specified for the inlet and outlet sections. It is assumed that the airfoil has a chord length of 1 meter.

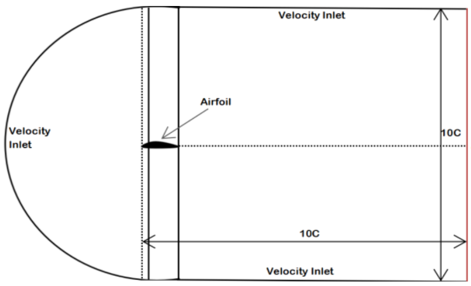


Fig-2: Computational Domain

The C-Mesh was created on entire domain. A mesh has been generated for the existing structural domain. The simulation incorporates the model's turbulence limit, and a smoothing algorithm is applied to enhance the balance of cells. To optimize computational efficiency and reduce processing time, the outer domain is meshed with a coarser cell edge length. Fig. 3 shows the structured mesh of the airfoil with C domain.

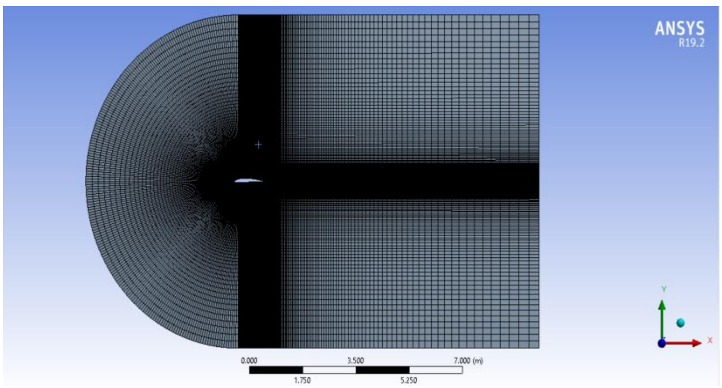


Fig-3: Mesh Generation

4.2 Boundary Conditions

Boundary conditions refer to the specified physical properties or conditions on the surfaces of domains, representing the flow variables of the intended physical model. In order to calculate and confirm the solver scheme, two airfoils were created with a chord length of 1 meter. The solution was executed with 1000 iterations for convergence. The solution method employed aims to achieve accurate results.

Table-1: Boundary Condition

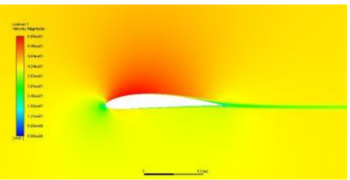
Input Parameter	Magnitude
Solver	Pressure Based
Viscous model	Spalart-Allmaras (1 eqn)
Gradient	Least squares cell based
Pressure	Second Order
Momentum	Second Order Upwind
Turbulent Viscosity	First Order Upwind
Viscosity	1.7894×105 kg/ms
Density of Fluid	1.225 kg/m3
Inlet Velocity	43.9 m/s
Reynold's number	3005336.98446
Cord Length	1 m

4.3 Results and discussion

In this section, we share the results of several simulations involving different angles of attack for NACA 4412 and NACA 23012 airfoils. These simulations were conducted using the ANSYS Fluent software, incorporating the necessary parameters.

4.3.1 Velocity Contour

The velocity contour provides detailed insights into the airflow over and beneath the airfoil, showing variations at different angles of attack.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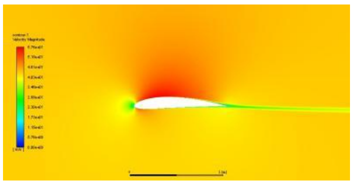
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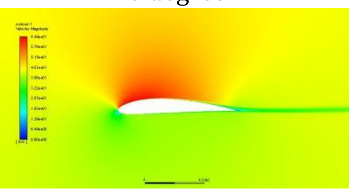
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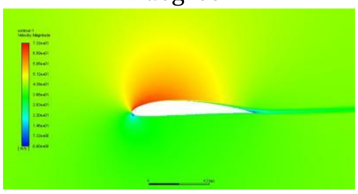
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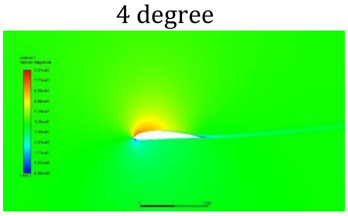
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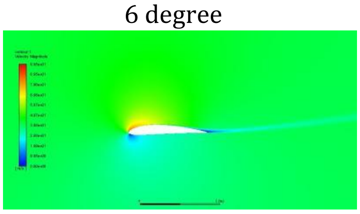
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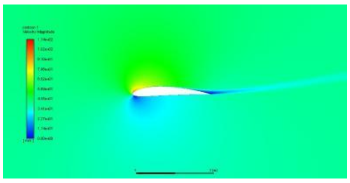
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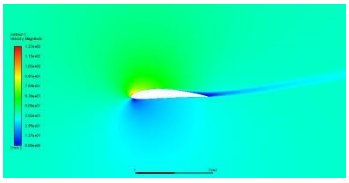
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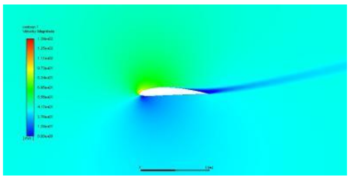
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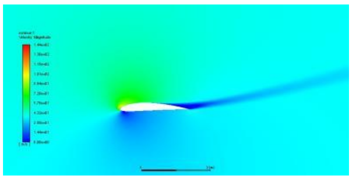
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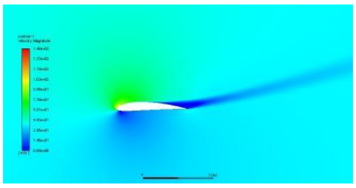
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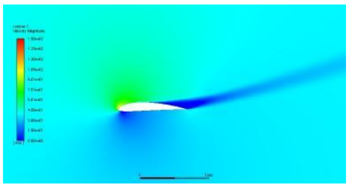
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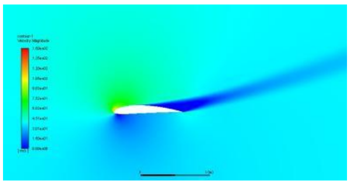
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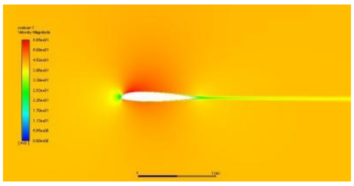
Fig-4: Velocity contour of **NACA 4412** airfoil at different angle of attack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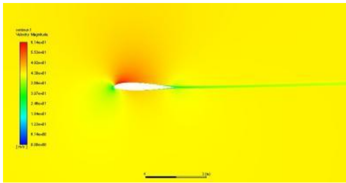
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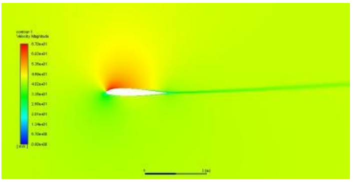
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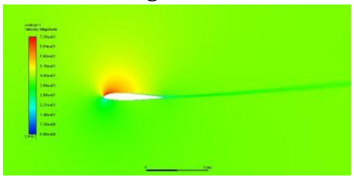
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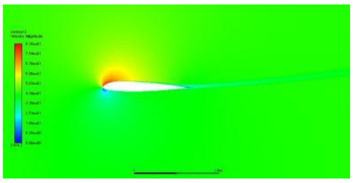
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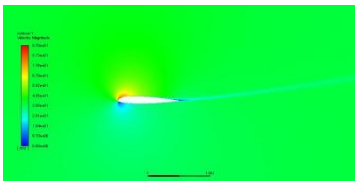
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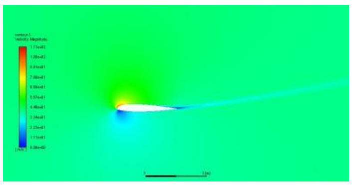
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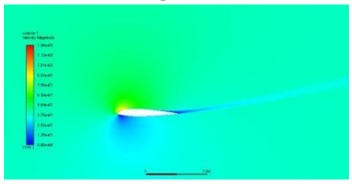
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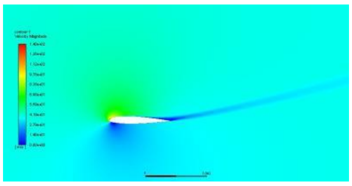
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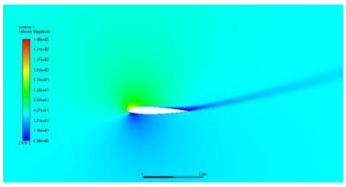
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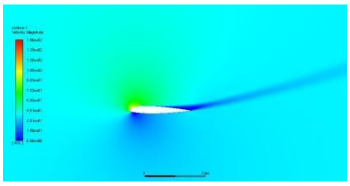
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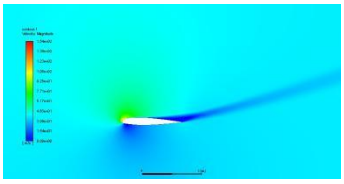
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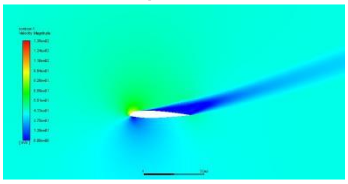

20 degree

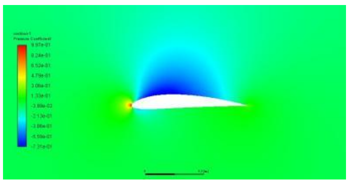
Fig-5: Velocity contour of **NACA 23012** airfoil at different angle of attack

The above Figs. 4 and 5 represent the velocity contours of NACA 4412 and 23012, which illustrate the effect of velocity in the upper and lower of the airfoil. As we can see, the velocity is high at the upper surface of the airfoil during a low angle of attack, which means that the pressure is low and the lift generation is high, according to Bernoulli's theory. At one point, when the angle of attack rises to the maximum angle or stall angle, the velocity decreases on the upper surface and increases on the lower side of the airfoil, which causes a drop in lift.

Regarding the trailing edge, it complies with the Kutta condition, stating that a body with a sharp trailing edge moving through a fluid will induce circulation sufficient to keep the rear stagnation point at the trailing edge. The flow pattern converges above and below the corner, meeting and then diverging from the body, creating a stagnation point at the trailing edge. With an increase in the angle of attack, the airflow over the upper surface of the airfoil becomes less smooth, causing the separation point to move from the trailing edge toward the leading edge.

4.3.2 Pressure Contour

Pressure contour refers to the distribution of pressure across the surface of an airfoil. It provides a visual representation of how air pressure varies at different locations on the airfoil's upper and lower surfaces. The pressure contour is typically depicted using a color map or contour lines on a graph.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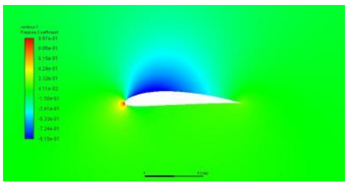
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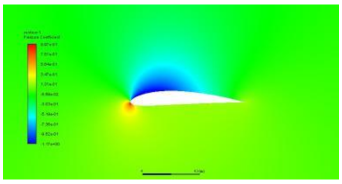
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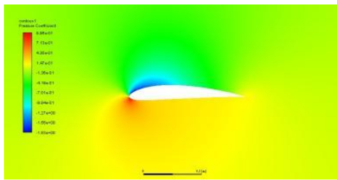
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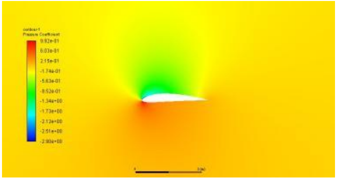
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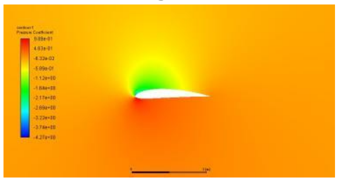
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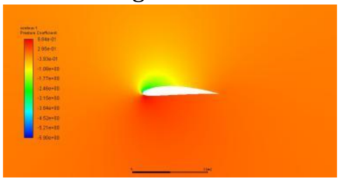
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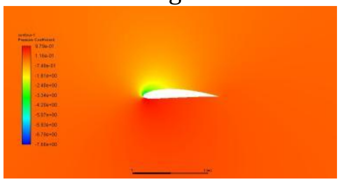
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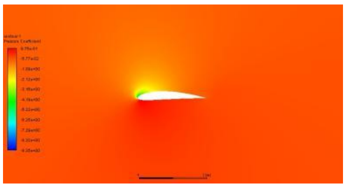
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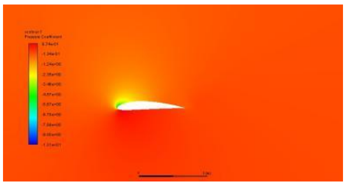
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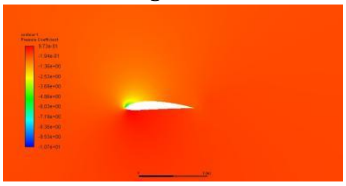
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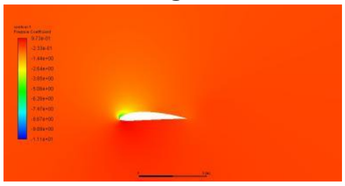
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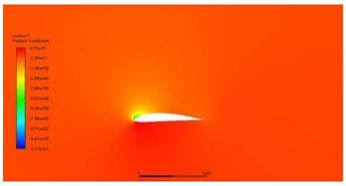
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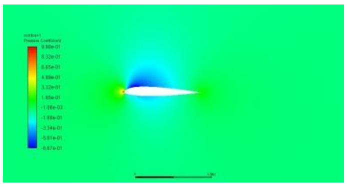
Fig-6: Pressure contour of **NACA 4412** airfoil at different angle of attack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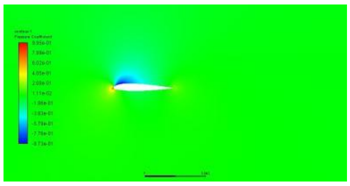
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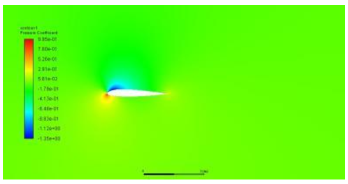
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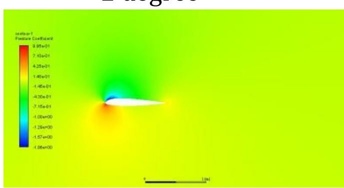
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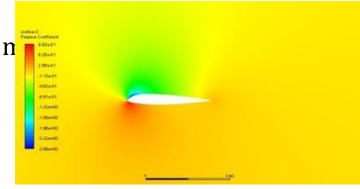

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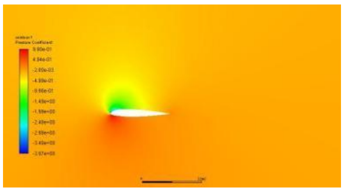

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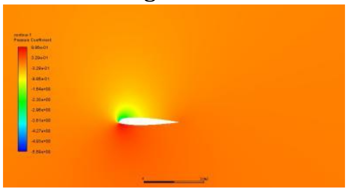

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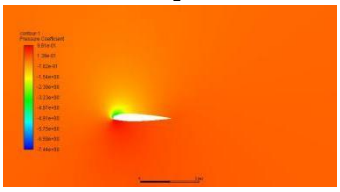

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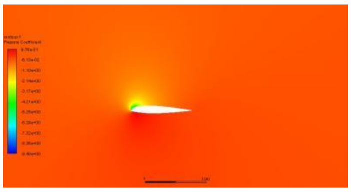

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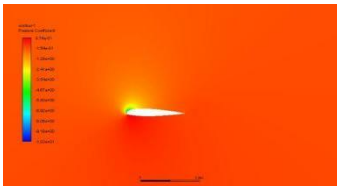

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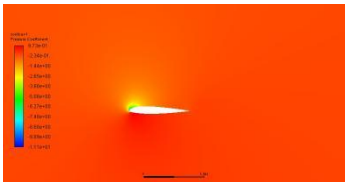

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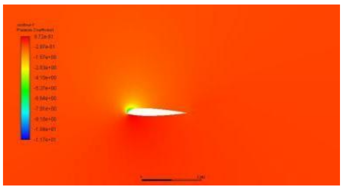

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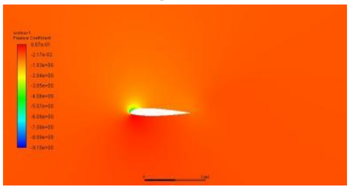

20 degree

Fig-7: Pressure contour of **NACA 23012** airfoil at different angle of attack

The above figs. 6 and 7 clearly illustrates how pressure coefficients vary across the airfoil at different angles of attack. Notably, at zero degree angle of attack, the leading edge shows a stagnation point with the highest static pressure. This emphasizes the influence of the angle of attack on pressure distribution along the airfoil. When the pressure at the upper surface of airfoil is less than bottom surface for incoming flow, the air can push upward effectively and generate lift. From Bernoulli's theorem, we know that total pressure is constant along this flow. Since then, we have concluded that dynamic pressure is higher at the upper surface due to higher velocity while the static pressure is less for a higher surface and more for a lower surface. From this computational investigation and simulation results, we verified Bernoulli's theorem. It also shows the difference in pressure is very significant only towards the leading edge. Thus, these regions contribute to lift generation to a great extent.

Since the flow separation occurred at 17° for the NACA 4412 airfoil while for the NACA 23012 it happened at 18°, the variation of the pressure coefficient on the surface for the stall angle of attack is shown below.

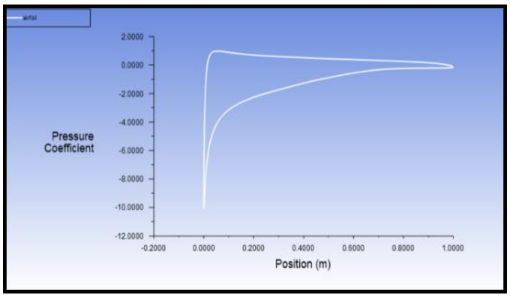

Fig-8: Variation of C_p along the surface of NACA 4412 airfoil at 17° angle of attack

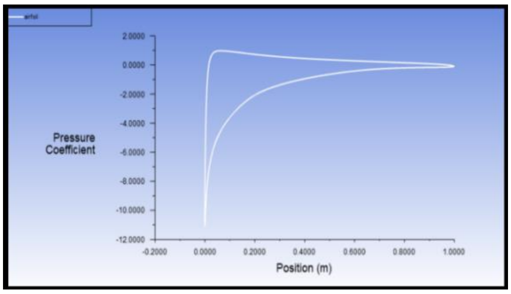

Fig-9: Variation of C_p along the surface of NACA 23012 airfoil at 18° angle of attack

4.3.3 Lift and Drag Coefficient

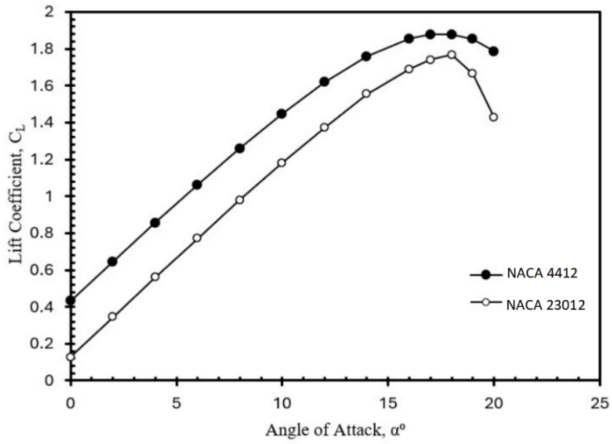

Fig-10: Lift co-efficient vs angle of attack

The figure above depicts the coefficient of lift variation at different angles of attack for NACA 4412 and NACA 23012 airfoils. Up to a 15-degree angle of attack, the lift curve is nearly linear for both airfoils, indicating attached flow without separation. However, at around 16 to 17 degrees, the upper surface flow on the airfoil starts to separate, leading to stall conditions. At the stall angle, the lift coefficient sharply decreases due to significant flow separation. Figure 10 confirms the critical angle of attack for NACA 4412 as 17° and for NACA 23012 as 18°. It's also observed that the NACA 4412 airfoil generates more lift compared to the NACA 23012 airfoil. Also the drag coefficient decrease when the airfoil is camber.

The drag coefficient quantifies the efficiency of a streamlined aerodynamic body in facilitating the forward motion of an airfoil. The variation of drag coefficient for different angles of attack of the NACA 4412 and 23012 airfoils is shown in Fig. 11.

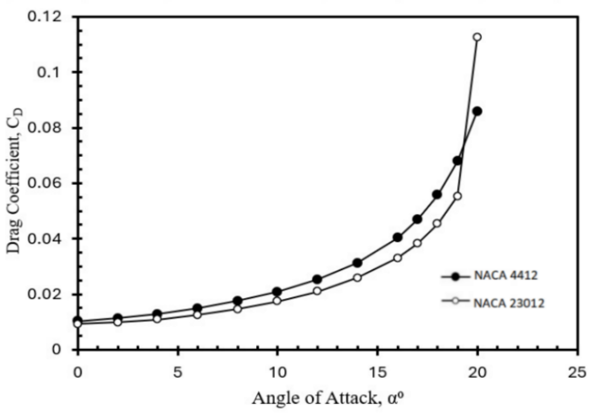

Fig-11: Drag co-efficient vs angle of attack

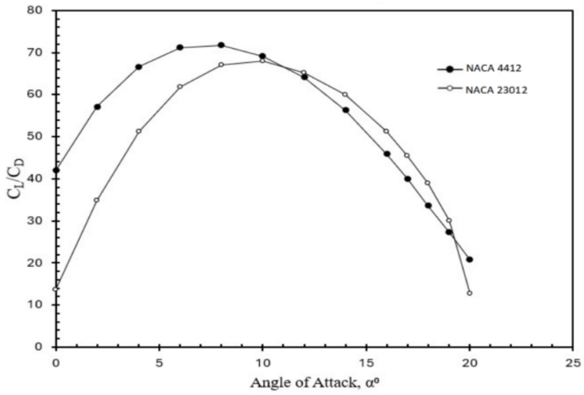

Fig-12: C_L/C_D vs angle of attack

Table-2: Lift and Drag Coefficient of NACA 4412 airfoil

Angle of Attack	C_L	C_D	C_L/C_D
0°	0.43078	0.010243	42.05439
2°	0.64415	0.011267	57.16881
4°	0.85564	0.012842	66.62575
6°	1.06144	0.014918	71.15009
8°	1.25932	0.017562	71.70744
10°	1.44604	0.020918	69.13900
12°	1.61736	0.025244	64.06867
14°	1.75832	0.031228	56.30426
16°	1.85354	0.040369	45.91505
17°	1.87733	0.046865	40.05757
18°	1.87693	0.055769	33.65526
19°	1.85188	0.067930	27.26127
20°	1.78602	0.085869	20.79926

Table-3: Lift and Drag Coefficient of NACA 23012 airfoil

Angle of Attack	C_L	C_D	C_L/C_D
0°	0.12729	0.00932	13.65106
2°	0.34384	0.00985	34.90621
4°	0.55906	0.01089	51.30830
6°	0.77186	0.01246	61.91397
8°	0.98006	0.01460	67.90707
10°	1.18157	0.01739	67.11662
12°	1.37171	0.02102	65.23944
14°	1.54495	0.02588	60.06088
16°	1.68899	0.03301	51.15353
17°	1.74052	0.03823	45.52396
18°	1.76796	0.04537	38.95951
19°	1.66351	0.05528	30.08943
20°	1.42561	0.11252	12.66925

CONCLUSION

This research focused on the comprehensive examination and comparison of the aerodynamic characteristics of the NACA 23012 and NACA 4412 airfoil profiles, employing the Spalart-Allmaras turbulence model. The study includes a detailed presentation of the NACA series, specifically highlighting the features of the NACA 4412 and 23012 airfoils, as well as elucidating the airfoil nomenclature. Computational analysis was conducted across various angles of attack (ranging from 0° to 20°) to visualize the alterations in lift coefficient, drag coefficient, and pressure distribution over the airfoil.
The paper encompasses all stages of the analysis process and incorporates a mathematical formula aimed at enhancing the comprehension of airfoil analysis. The obtained results from the analysis of NACA 4412 and 23012 were meticulously compared and subsequently presented through graphical representations. These visual representations indicate that the NACA 4412 airfoil demonstrates a higher lift coefficient at all angles of attack when juxtaposed with the NACA 23012 airfoil. However, it was observed that the stall angle for the NACA 4412 airfoil is marginally less than that of the NACA 23012 airfoil, specifically measuring 17° and 18°, respectively.

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We extend our sincere appreciation to Dr. P. Karunakaran, Head of the Department, Department of Aeronautical Engineering, for the generous support and resources provided by Excel Engineering College. Special recognition is also due to M. Sanjay sir for his invaluable guidance and continuous supervision, significantly enhancing the quality of this research. Lastly, our gratitude goes to all the faculty members for their constructive feedback and insightful contributions at various stages of this research.

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