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Aerodynamic Study on Low Reynolds Number Aerofoil

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Abstract - *Low Reynolds number refers to a specific range of values of the dimensionless parameter known as the Reynolds number (Re) in fluid dynamics. The Reynolds number is a critical factor used to characterize and predict fluid flow behaviour around objects or within fluid systems. Low Reynolds numbers (typically Re < 2000), laminar flow prevails, where fluid particles move in smooth, orderly layers with minimal mixing or turbulence. Low Reynolds number aerodynamics is a focal point of interest, especially for micro air vehicles (MAVs), drones, and small-scale aircraft. Understanding the nuanced aerodynamic performance of aerofoils and wings in this regime is pivotal for designing efficient and controllable flight systems, ushering in innovations in the field of aviation. The unique characteristics of low Reynolds number flow to advance technology, science, and our understanding of fluid dynamics.*

I INTRODUCTION

The Re is a dimensionless parameter which plays a important role in understanding the behaviour of fluids, including air and water, as they flow around objects. It was first introduced by the British scientist Osborne Reynolds in the late 19th century. Reynolds conducted pioneering experiments involving the flow of fluid in pipes and made significant contributions to our understanding of fluid dynamics.

The Re is expressed as:

$$Re = (\rho * V * L) / \mu$$

Where

ρ (rho) - Fluid density
V - Fluid Velocity
L is a characteristic length
μ (mu) is the dynamic viscosity of the fluid

The Re serves as a critical parameter for predicting and categorizing the flow regime around an object or within a fluid system. Its significance in aerodynamics and fluid mechanics can be summarized as follows:

1. Flow Classification: The Reynolds number helps classify fluid flows into different regimes. These regimes include Laminar Flow ($Re < 2000$), Transition Flow ($2000 < Re < 4000$) and Turbulent Flow ($Re > 4000$). Turbulent flows exhibit eddies, swirls, and enhanced mixing. They are characterized by increased drag and energy loss.
2. Aerodynamic Performance: The Rer significantly affects the aerodynamic performance of aircraft, aerofoils, and other objects moving through a fluid. For example: In aviation, aircraft wings and aerofoils experience different lift and drag characteristics depending on the Reynolds number. Understanding this variation is essential for designing efficient and stable flight.

3. Low Reynolds numbers are relevant for micro-scale flight, drones, and small Unmanned Aerial Vehicles (UAVs). At these scales, the effects of viscous forces become more pronounced and can significantly impact flight performance and the effects of Reynolds number for different airfoil is shown in Figure 1. Heat Transfer: The Reynolds number is also critical in the study of heat transfer. It affects the convective heat transfer coefficient and the overall thermal performance of systems such as heat exchangers and cooling systems.

4. Engineering and Design: Engineers use the Reynolds number to design and optimize various fluid systems, including pipes, pumps, and heat exchangers. It guides decisions on flow regimes, pipe sizes, and the selection of appropriate equipment.

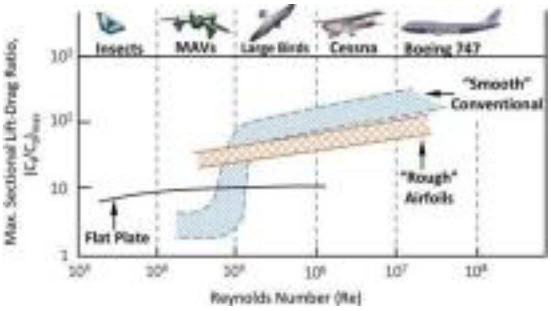

Figure 1 Effect of Reynolds Number on Airfoil [2] and [3]

A. Importance of Studying Low Reynolds Number Aerofoils and their Applications

Studying low Reynolds number aerofoils and their applications, such as in micro air vehicles (MAVs), drones, and small-scale aircraft, holds immense importance due to the unique challenges and opportunities they present. Here's a detailed explanation of their significance:

1. **Efficient Flight in Constrained Environments**

- Low Reynolds number aerofoils are particularly relevant in the design of MAVs, drones, and small-scale aircraft, where size and weight constraints are critical. These vehicles often operate in confined spaces, making efficient aerodynamics essential.
- Understanding low Reynolds number air foil behaviour allows engineers to design wings and aerofoils that provide the necessary lift while minimizing drag. This optimization results in longer flight endurance and improved mission capabilities

2. **Improved Manoeuvrability and Control**

- Precise control is crucial for small-scale aircraft that need to navigate through complex environments or perform specific tasks. Low Reynolds number aerofoils exhibit unique control characteristics influenced by viscous forces.
- Research in this area helps develop control systems tailored to these characteristics, enabling enhanced manoeuvrability and control precision, making them suitable for various applications, including surveillance, agriculture, and search and rescue.

3. Reduced Noise and Environmental Impact

- Low Reynolds number aerofoils can be designed to minimize noise and environmental impact. Quieter flight is crucial in applications like urban surveillance, where noise pollution is a concern.
- Enhanced aerodynamics and efficiency can also lead to reduced energy consumption, contributing to environmental sustainability in small-scale aviation.

4. Microfluidics and Lab-on-a-Chip Devices

- Low Reynolds number principles extend beyond aviation. They are essential in microfluidics, where precise control of fluids on a tiny scale is necessary for applications like medical diagnostics, drug delivery, and chemical analysis.
- Aerofoil research in low Reynolds number conditions informs the design of microfluidic devices and enhances their performance.

5. Biologically-Inspired Designs

- Nature often operates in low Reynolds number environments, such as the motion of cilia and flagella in biological systems. Studying low Reynolds number aerofoils can inspire biomimetic designs for propulsion and sensing systems in robotics and autonomous vehicles.

6. Fundamental Understanding of Fluid Dynamics

- Research in low Reynolds number aerodynamics contributes to our fundamental understanding of fluid dynamics. It provides insights into the change from laminar flow to turbulent, boundary layer behaviour, and the effects of viscous forces.
- These insights are valuable not only for specific applications but also for advancing the broader field of fluid mechanics and engineering.

B. Low Reynolds Number Aerofoils

NACA 0009: this aerofoil has a maximum thickness of 9% of the chord length. The aerofoil is symmetric, meaning that the upper and lower surfaces are identical in shape. The NACA 0009 aerofoil is commonly used in many applications, including wind turbines and hydrofoils.

NACA 0012: This aerofoil is commonly used in wind turbines and has a maximum thickness of 12% of the chord length.

NACA 4412: This aerofoil is used in many applications, including aircraft wings and hydrofoils, and has a maximum thickness of 12% of the chord length.

NACA 23012: This aerofoil is used in many applications, including wind turbines and hydrofoils, and has a maximum thickness of 12% of the chord length.

Eppler 387: This aerofoil is used in many applications, including sailplanes and wind turbines, and has a maximum thickness of 12.5% of the chord length

C. Present Development in Low Reynolds Number Aerofoil

At low Reynolds numbers, which are characteristic of slow-moving or small-scale flow, the behaviour of aerofoils can differ significantly from what is observed at higher

Reynolds numbers. Here are some key developments in the study and design of aerofoils for low Reynolds number conditions:

Aerofoil Shapes: Aerofoils designed for low Reynolds numbers often feature thicker profiles compared to those used at higher Reynolds numbers. This helps to delay flow separation and maintain lift at lower speeds.

Boundary Layer Control: Techniques such as boundary layer suction or blowing can be employed to control the boundary layer and delay separation, improving the aerodynamic performance of the aerofoil.

Experimental Studies: Experimental studies, including wind tunnel test is used to understand the flow behaviour around low Reynolds number aerofoils and to optimize their design.

High-Lift Devices: High-lift devices such as flaps and slats are often used to enhance the lift characteristics of low Reynolds number aerofoils, allowing aircraft to operate at lower speeds during take-off and landing.

Control Surface Design: The design of control surfaces such as ailerons, elevators, and rudders are crucial for effective control of aircraft at low Reynolds numbers, where the flow around these surfaces can be significantly different from that at higher Reynolds numbers.

Numerical Simulations: Advances in numerical simulations, particularly in the area of high-fidelity CFD, have enabled researchers to better understand the complex flow phenomena associated with low Reynolds number aerofoils and to develop improved design methodologies.

Application in UAVs: Low Reynolds number aerofoils are commonly used in the design of small UAVs and micro air vehicles due to their ability to generate lift at low speeds and their suitability for small-scale applications.

Bio-Inspired Designs: Some researchers have looked to nature for inspiration, studying the aerodynamics of bird and insect wings to develop more efficient low Reynolds number aerofoils.

II LITERATURE SURVEY

[1] focused on the low Reynolds number aerofoil performance (How aerofoils behave at low Reynolds numbers, including their lift and drag characteristics. This could include discussions of the stall behaviour, which can be particularly important for low Reynolds numbers.), flow separation (how flow separation occurs at low Reynolds numbers and how it affects aerofoil performance. Understanding separation and reattachment phenomena is crucial for designing efficient aerofoils.), aerodynamic coefficient (data and graphs related to the lift coefficient (Cl) and drag coefficient (Cd) as functions of angle of attack and Reynolds number.) and boundary layer effect (boundary layer behaviour and its impact on aerofoil performance at low Reynolds numbers. Boundary layer separation and transition can significantly influence aerodynamic properties.).

[2] discussed Aerofoil Design Considerations (The specific considerations and challenges associated with designing aerofoils for micro aerial vehicles that operate at low Re. This may include factors such as size, weight, and performance requirements.), Reynolds

Number Effects (the aerodynamic effects of operating at low Reynolds numbers, which can significantly impact aerofoil performance. Understanding these effects is crucial for designing efficient MAVs.) and Numerical Methods and Simulations (the use of computational tools and simulations to design and analyse aerofoils. This could include details about the software and methodologies employed.).

[3] focused on low Reynolds number Aerofoil Design Criteria (The specific design criteria and considerations when developing aerofoils for unmanned aerial vehicles (UAVs) that operate at low Reynolds numbers. These considerations could include the need for high lift, stability, and efficiency.), Aerodynamic Performance (The aerodynamic performance of the designed aerofoils, including lift and drag characteristics, as well as how these aerofoils perform under different flight conditions.) and Comparisons and Optimization (Comparing different aerofoil designs and optimization strategies to highlight the most suitable configurations for UAVs operating under low Reynolds number conditions.).

[4] surveyed different types of low Reynolds number aerofoil and they take Survey of Existing Low Reynolds Number Aerofoils (An extensive survey and summary of existing low Reynolds number aerofoils. It may categorize and describe various aerofoils, their characteristics, and their historical development.), Performance Characteristics (the aerodynamic performance characteristics of low Reynolds number aerofoils, including lift and drag coefficients, stall behaviour, and other relevant properties.) and Design Trends (design trends and considerations specific to low Reynolds number aerofoils. This could include design challenges and strategies to address them.).

[5] focused on Design Methodology (designing low Reynolds number wings for unmanned aerial vehicles (UAVs). It may explain the criteria and constraints considered during the design process.), Aerofoil Selection (he selection of specific aerofoil shapes or aerofoil profiles suitable for low Reynolds number conditions. It might provide insights into why certain profiles were chosen.) and Case Study Details (the specific UAV or application for which the wing was designed. This could include the UAV's mission requirements, size, weight, and intended operational conditions.).

III PROBLEM STATEMENT

High Viscous Drag: In low Reynolds number flow, the effect of viscosity is pronounced, leading to higher viscous drag forces. This can be problematic for many applications, such as small-scale unmanned aerial vehicles (UAVs) or microfluidic devices, where minimizing drag is essential for efficiency and manoeuvrability.

Effects of Reynolds Number: Investigate how changes in Reynolds number impact the aerodynamic performance and flow behaviour of the aerofoil.

Effect of Aerofoil Geometry: Examine the influence of aerofoil geometry parameters such as aerofoil thickness, camber, and aspect ratio on aerodynamic performance.

Comparison with High Reynolds Number Data: Compare the findings from low Reynolds number aerofoil with existing data for higher Reynolds numbers to identify scaling effects and deviations in aerodynamic behaviour.

Boundary Layer Growth: At low Reynolds numbers, boundary layers adjacent to solid surfaces tend to grow thicker, which can affect the performance of aerodynamic or hydrodynamic surfaces. Thick boundary layers can lead to flow separation and reduced lift generation on aerofoils

IV OBJECTIVES

- The primary objective of this study is to investigate and understand the aerodynamic behaviour of aerofoils at low Reynolds numbers, with a focus on providing insights into their performance characteristics, lift and drag coefficients, and flow patterns.
- Analysis of selected low Reynolds number aerofoil using ANSYS software and using MAT LAB and X-FOIL
- Comparing NACA 0009 and NACA 2412

V METHODOLOGY

A. Preprocessing Work

Data collection: We identifying and gather relevant data and information from various sources, such as research papers technical documents and reputable scientific publications. Ensuring that the data collected aligns with the specific objectives and requirements of the project.

Data cleaning: We reviewed and cleaned the collected data to remove any inconsistencies, errors and irrelevant information

Data organizing: We organized the collected data in a structured manner, and created easy method design and analysis of low Reynolds number aerofoil

Data integration: We worked with the multiple data sources, merged and integrated the data we created to be unified dataset

Data validation: We validated the collected data is accuracy and reliability according to our project.

B. Types of software used in this project

1. ANSYS
2. X-FOIL
3. MAT LAB

C. Brief Methodology of ANSYS Software

Studying aerodynamics at low Reynolds numbers can be challenging due to the unique flow characteristics associated with these conditions. Low Reynolds numbers typically correspond to flow regimes where viscous forces dominate. Here's a general methodology for conducting aerodynamic studies on low Reynolds number aerofoils:

1) Literature Review: Begin by reviewing relevant literature on low Reynolds number aerodynamics. Identify key studies, experimental techniques, and numerical simulations that have been conducted on similar aerofoils. Understand the challenges and limitations associated with low Reynolds number flows.

2) Aerofoil Selection: Choose a specific aerofoil or a set of aerofoils suitable for low Reynolds number conditions. Aerofoils with documented performance in low Reynolds number regimes or designed specifically for such conditions are preferable.

The chosen aerofoil for aerodynamic study is NACA 0009. The NACA 0009 aerofoil is considered a low Reynolds number aerofoil. According to a numerical study on the aerodynamic characteristics of the NACA 0018 aerofoil, which is similar to the NACA 0009 aerofoil, the laminar boundary layer on the upper surface of the aerofoil is prone to separation in the range of Reynolds numbers between 10,000 and 106. For Reynolds numbers below 30 ×103, the flow does not reattach, but a wide wake is visible behind the aerofoil.

3) Generating geometry and meshing of aerofoil: The model of the aerofoil, domain, mesh details and boundary conditions are given in Figure 1 and 2 respectively.

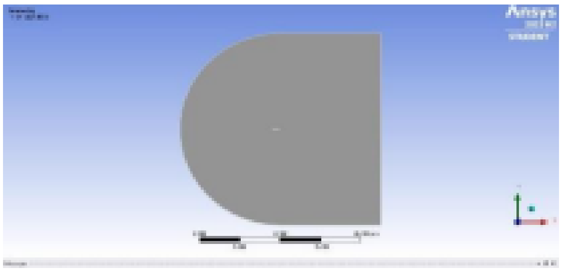

Figure 1 Geometry of NACA0009 AEROFOIL

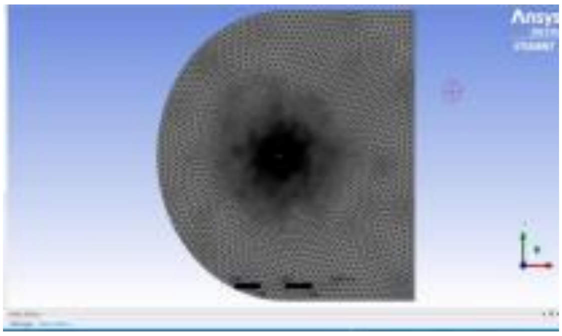

Figure 2 Meshing of above geometry

4) Flow Visualization: Employ flow visualization techniques to understand the behaviour of the flow over the aerofoil. This could include the use of smoke visualization, tuft testing, or other methods to qualitatively analyse the flow patterns.

5) Data Analysis: Analyse the collected data to determine the lift and drag coefficients, stall characteristics, and other relevant aerodynamic parameters.

6) Correlation and Modelling: 5.1278 Develop correlations or empirical models based on the obtained data. These models can be used for predicting aerofoil performance at different operating conditions within the low Reynolds number range. And same repeated for the NACA 2412 aerofoil to compare with the NACA 0009 aerofoil.

D. Brief Methodology to Analyse an Aerofoil using XFOIL

1. **Aerofoil Definition:** Define the aerofoil geometry in XFOIL using the NACA 0009 code (NACA 0009) or by specifying custom coordinates if available [6].
2. **Operational Setup:** Set the desired operational conditions such as Reynolds number (RE) and Mach number (MACH). For example, to set the Reynolds number to 1 million, you would use RE 1000000.
3. **Analysis:** Perform the desired analysis, such as computing the pressure distribution, lift and drag coefficients, or polar plots. For example, to analyse the aerofoil at an angle of attack of 5 degrees, you would use ALFA 5.
4. **Visualization:** Visualize the results using XFOIL's built-in plotting capabilities. For example, use PANE to plot the pressure distribution or CPWR to plot the coefficient of pressure distribution.
5. **Iterative Analysis:** Optionally, perform iterative analysis by varying parameters such as Angle Of Attack (AOA), Re, or flap deflection (FLAP) to study the aerofoil's performance over a range of conditions.
6. **Save Results:** Save the results of your analysis for further examination or comparison. Here is an example of a session in XFOIL to analyse a NACA 0009 aerofoil at a Reynolds number of 1 million and an angle of attack of 5 degrees:
   NACA 0009, OPER, RE 1000000, ALFA 5, PANE, CPWR

This is a basic example, and the specific commands and options may vary depending on analysis requirements. And same repeated for the NACA 2412 aerofoil to compare with the NACA 0009 aerofoil.

E. Brief Methodology for Analysing an Aerofoil using MATLAB

1. Aerofoil Geometry: Generate the coordinates of the NACA 0009 aerofoil using the NACA 4-digit series equations. The code generates the coordinates of a NACA 0009 and 2412 aerofoil using the NACA 4-digit series equations and plots its geometry.

2. Geometric Analysis: Analysing the geometric properties of an aerofoil, such as chord length, camber, thickness distribution, and leading/trailing edge shapes.

Analysing the geometric properties of a NACA 0009 aerofoil in MATLAB involves calculating various parameters such as chord length, camber, thickness distribution, and leading/trailing edge shapes. Code calculates the x and y coordinates for both the upper and lower surfaces of the aerofoil based on the NACA 4-digit series equations.

3. Potential Flow Theory: Use potential flow theory to calculate the lift and drag coefficients for the aerofoil at different angles of attack. The lift coefficient can be calculated using thin aerofoil theory (e.g., lifting-line theory).

MAT LAB code calculates the lift and drag coefficients for a NACA 0009 and 2412 aerofoil at different angles of attack using potential flow theory and thin aerofoil theory. The lift and drag coefficients are plotted against the angle of attack.

4. Polar Plot: Create polar plots showing the variation of Lift Coefficient (CL) and Drag Coefficient (CD) with AOA.

MAT LAB code calculates the lift and drag coefficients for a NACA 0009 aerofoil at different angles of attack using potential flow theory and thin aerofoil theory. It then creates polar plots showing the variation of CL and CD with alpha.

5. Pressure Distribution: Calculate and visualize the pressure distribution around the aerofoil. To calculate and visualize the pressure distribution around a NACA 0009 aerofoil. AT LAB code calculates the pressure Coefficient (Cp) at each panel on the aerofoil and hen plots the pressure distribution

6. Structural Analysis: Perform a structural analysis of the aerofoil to study its behaviour under aerodynamic loads.

Performing a structural analysis of an aerofoil to study its behaviour under aerodynamic loads typically involves calculating the lift and drag forces acting on the aerofoil and then analysing the structural response of the aerofoil under these loads. Since this is a simplified analysis, we can use the lift and drag coefficients calculated using potential flow theory and thin aerofoil theory, and assume a simple structural model for the aerofoil.

7. Animation: Create animations to visualize the aerodynamic characteristics and flow behaviour around the aerofoil.

To create animations to visualize the aerodynamic characteristics and flow behaviour around a NACA 0009 aerofoil, use potential flow theory to calculate the flow field and then visualize it using streamlines

8. Comparison: Compare the aerodynamic characteristics of the NACA 0009 aerofoil with . NACA 2412 aerofoils or configurations to evaluate performance differences.

This methodology provides a basic framework for analysing the aerodynamic characteristics of a NACA 0009 aerofoil using MATLAB.

VI RESULTS AND DISCUSSION

A. Introduction

Here we are discussing about the results of both NACA 0009 and NACA 2412 aerofoil analysed by using 3 different software's like ANSYS, MAT LAB and X-FOIL software.

1. Results got by the analysis of the NACA 0009 and NACA 2412 aerofoils using MATLAB.

NACA 0009 Aerofoil

The NACA 0009 aerofoil, being symmetric, exhibits typical behaviour for a symmetric aerofoil. At low Angles Of Attack (AoA), the Lift Coefficient (CL) remains low, indicating minimal lift generation. As the AoA increases, the CL also increases until it reaches a maximum value, after which it decreases sharply due to flow separation and stall. The Drag Coefficient (CD) remains relatively low at low AoA but increases significantly after stall, indicating a loss in aerodynamic efficiency.

NACA 2412 Aerofoil

In contrast, the NACA 2412 aerofoil, with its cambered shape, exhibits different aerodynamic characteristics. Even at low AoA, the aerofoil generates lift, thanks to its camber. The lift coefficient increases more gradually with AoA compared to the NACA 0009 aerofoil. The camber helps maintain attached flow over a wider range of AoA, resulting in a delayed stall compared to the NACA 0009 aerofoil.

2. Results got by the analysis of the NACA 0009 and NACA 2412 aerofoils using ANSYS

Using ANSYS software, we analysed the aerodynamic performance of NACA 0009 and NACA 2412 aerofoils at different angles of attack. The lift and drag coefficients were computed for each aerofoil, and velocity contours were visualized to understand the flow behaviour.

The results show that the NACA 0009 aerofoil, being symmetric, exhibits predictable aerodynamic behaviour. At low angles of attack, it produces minimal lift and drag, consistent with its symmetric profile. As the angle of attack increases, the lift coefficient rises until reaching a maximum, after which it sharply decreases due to stall. The drag coefficient remains relatively low until stall, where it increases significantly. This behaviour is typical of symmetric aerofoils, where flow separation occurs near the trailing edge at high angles of attack.

3. Results got by the analysis of the NACA 0009 and NACA 2412 aerofoils using X FOIL

NACA 0009 Aerofoil

Using XFOIL, we analysed the NACA 0009 aerofoil at various Angles of Attack (AoA) to determine its aerodynamic characteristics. The lift coefficient (CL) curve shows a typical symmetric aerofoil behaviour, with CL increasing linearly with AoA up to a certain point, beyond which it sharply decreases due to stall. The drag coefficient (CD) curve remains relatively low at low AoA but increases significantly post-stall. The aerofoil exhibits well defined stall behaviour, typical of symmetric aerofoils.

NACA 2412 Aerofoil

For the NACA 2412 aerofoil, XFOIL analysis revealed a different aerodynamic behaviour. The cambered aerofoil exhibited higher lift coefficients at lower AoA compared to the NACA 0009 aerofoil, thanks to its camber. The lift curve showed a gradual increase in CL with AoA, and the stall occurred at a higher AoA compared to the NACA 0009 aerofoil. This delayed stall behaviour is characteristic of cambered aerofoils, where the camber helps maintain attached flow over a wider AoA range.

The analysis of NACA 0009 and NACA 2412 airfoils using MATLAB, ANSYS, and XFOIL revealed distinct aerodynamic behaviors. The NACA 0009, being symmetric, shows low lift and drag at low angles of attack, with a sharp increase and then decrease in lift coefficient at higher angles, indicating stall. The NACA 2412, with its camber, generates lift even at low angles, with a more gradual increase in lift coefficient and a delayed stall compared to the NACA 0009. ANSYS analysis confirmed these trends, providing further insights into the aerodynamic performance of these airfoils. Cambered airfoils like the NACA 2412 offer advantages in lift generation and stall characteristics compared to symmetric airfoils like the NACA 0009, making them suitable for different aircraft design requirements.

Computational tools like MATLAB, ANSYS, and XFOIL play a crucial role in analyzing and predicting the aerodynamic performance of airfoils, providing valuable insights for aircraft designers and engineers.

B. Result and Discussion of ANSYS Fluent Flow

Velocity Counter of NACA 0009 and 2412

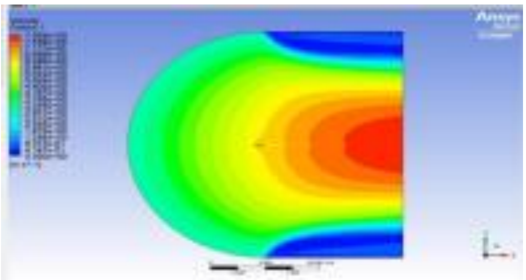

Figure 3 Velocity Counter of NACA 0009 Aerofoil

Flow Acceleration: The velocity contour around the NACA 0009 aerofoil shows that the flow accelerates over the upper surface, reaching maximum velocity near the leading edge and it is represented in Figure 3. This acceleration creates lower pressure on the upper surface, contributing to lift generation. The velocity gradually decreases along the upper surface towards the trailing edge.

Flow Deceleration: On the lower surface, the flow is relatively uniform with less velocity compared to the upper surface. The velocity contour shows a smooth transition of flow from the lower to the upper surface near the trailing edge.

Stagnation Point: The velocity at the stagnation point (on the air foil's leading edge) is zero, as this is where the flow splits to travel around the upper and lower surfaces of the aerofoil.

Boundary Layer Behaviour: The velocity gradient along the upper surface becomes steeper as the angle of attack increases, indicating a more critical flow condition and potential for boundary layer separation. This could lead to an increase in drag and a decrease in lift at higher angles of attack.

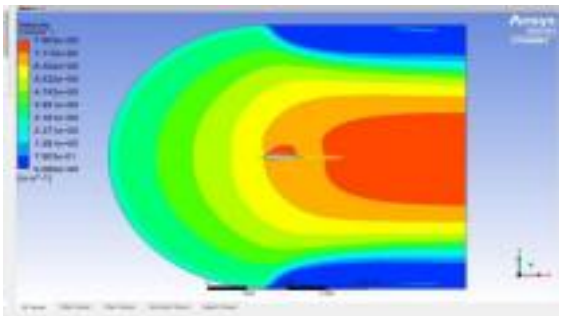

Figure 4 Velocity Counter of NACA 2412 Aerofoil

Flow Acceleration: The velocity contour plot shows that the flow accelerates over the upper surface of the NACA 2412 aerofoil, particularly near the leading edge and it is represented in Figure 4. This acceleration is a result of the aerofoil shape, which causes the flow to follow a longer path over the upper surface, leading to lower pressure and higher velocity according to Bernoulli's principle.

Smooth Flow Transition: The velocity contours also indicate a smooth transition of flow from the upper to the lower surface near the trailing edge. This indicates aerofoil is operating efficiently, with minimal flow separation. comparison of the NACA 0009 and NACA 2412 aerofoils, we need to consider various factors such as lift and drag coefficients, pressure distribution, and velocity profiles. For the velocity contour information, we will focus on the flow field around the aerofoils at different angles of attack (5, 10, and 15 degrees) with an inlet velocity of 3.

Velocity Contour Information

NACA 0009 Aerofoil

Angle of Attack = 5 Degrees

The velocity contour around the NACA 0009 aerofoil at 5 degrees AOA shows that the flow accelerates over the upper surface, reaching high velocity near the leading edge.

This acceleration creates lower pressure on the upper surface, contributing to lift generation. The velocity gradually decreases along the upper surface towards the trailing edge.

On the lower surface, the flow is relatively uniform with lower velocities compared to the upper surface. The velocity contour shows a smooth transition of flow from the lower to the upper surface near the trailing edge.

Angle of Attack = 10 Degrees

Degrees at 10 degrees angle of attack, the velocity contour around the NACA 0009 aerofoil exhibits a similar pattern to the 5 degrees case but with higher velocities on the upper surface due to increased angle of attack. The flow separation point may start to move towards the leading edge, indicating a potential stall condition.

Angle of Attack = 15 Degrees

The velocity contour at 15 degrees angle of attack shows further acceleration of flow over the upper surface, particularly near the leading edge. This acceleration is more pronounced compared to lower angles of attack, leading to higher lift production. However, the velocity gradient along the upper surface becomes steeper, indicating a more critical flow condition.

NACA 2412 Aerofoil

Angle of Attack = 5 Degrees

The velocity contour around the NACA 2412 aerofoil at 5 degrees angle of attack shows a similar pattern to the NACA 0009 aerofoil but with slightly lower velocities on the upper surface. The flow separation point is likely to be further back compared to the NACA 0009 aerofoil, indicating a more forgiving stall behaviour.

Angle of Attack = 10 Degrees

At 10 degrees angle of attack, the velocity contour around the NACA 2412 aerofoil exhibits increased velocities on the upper surface, but the flow separation point remains relatively stable. This indicates that the aerofoil is operating efficiently without approaching stall conditions.

Angle of Attack = 15 Degrees

The velocity contour at 15 degrees angle of attack shows further acceleration of flow over the upper surface, similar to the NACA 0009 aerofoil. However, the flow separation point on the NACA 2412 aerofoil is expected to be further back compared to the NACA 0009 aerofoil, indicating better stall characteristics.

Comparison and Discussion

The velocity contour information highlights the differences in flow behaviour between the NACA 0009 and NACA 2412 aerofoils. The NACA 0009 aerofoil tends to exhibit higher velocities and more pronounced flow acceleration over the upper surface, leading to higher lift but also higher drag compared to the NACA 2412 aerofoil. The NACA 2412 aerofoil, on the other hand, shows slightly lower velocities on the upper surface but maintains smoother flow patterns and delayed flow separation, indicating better stall characteristics and potentially higher lift-to-drag ratios.

These differences in flow behaviour are crucial for understanding the aerodynamic performance of the aerofoils and can help in selecting the most suitable aerofoil for specific applications based on the desired balance between lift and drag.

By analysing the velocity contours, we gain insights into how the flow behaves around the aerofoils at different AOA, providing a deeper understanding of their aerodynamic characteristics. The coefficients of lift and drag at different AOA for NACA 0009 and NACA 2412 are listed in Table 1. This information can be used to optimize the design of aerofoils for various applications, ensuring efficient and stable performance in different operating conditions.

Table 1 Lift and Drag Coefficient for Different AOA

Aerofoil	AOA (Degrees)	CL	V
NACA 0009	5	0.13369	2.6954
	10	0.46402	1.0641
	15	1.1212	5.1278
NACA 2412	5	0.31297	0.074646
	10	0.31298	0.074646
	15	0.31298	0.074646

C. Result and Discussion of X-FOIL Analysis

The analysis of the NACA 0009 and NACA 2412 aerofoils using XFOIL provided valuable insights into their aerodynamic performance characteristics.

NACA 0009 Aerofoil

The NACA 0009 aerofoil, being symmetric, exhibited the expected behaviour with respect to angle of attack (AoA). At low AoA, the aerofoil produced minimal lift and drag, consistent with its symmetric profile. As AoA increased, the lift coefficient (CL) rose steadily until reaching a maximum, after which it sharply decreased due to stall. The drag coefficient (CD) remained relatively low until stall, where it increased significantly. This behaviour is typical of symmetric aerofoils, where flow separation occurs near the trailing edge at high AoA.

In contrast, the NACA 2412 aerofoil, with its cambered profile, displayed a different aerodynamic response. Even at low AoA, the aerofoil generated lift due to its camber, which gradually increased with AoA. The camber helped maintain attached flow over a wider range of AoA, resulting in a delayed stall compared to the NACA 0009 aerofoil. This characteristic is beneficial for applications requiring higher lift at lower speeds.

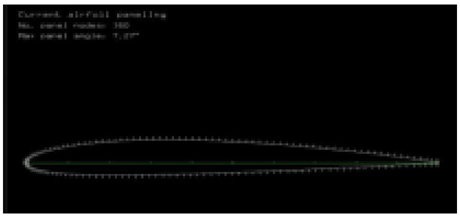

Figure 5 X-Foil Geometry of NACA 0009 Aerofoil

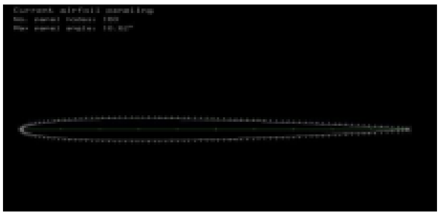

Figure 6 X-Foil Geometry of NACA 2412 Aerofoil

Comparison

The X-Foil geometry of NACA 0009 and NACA 2412 aerofoil and comparison of both the X-Foil geometry are shown in Figure 5 and 6 respectively. Comparing the two aerofoils, the NACA 2412 aerofoil exhibited higher lift coefficients at lower AoA, thanks to its camber, making it suitable for applications where higher lift is needed at lower speeds. On the other hand, the NACA 0009 aerofoil, with its symmetric profile, is more suitable for applications where a balance between lift and drag is critical. The pressure coefficient of different AOA with 0.5 degree increment for NACA 0009 is shown in the Figure 7.

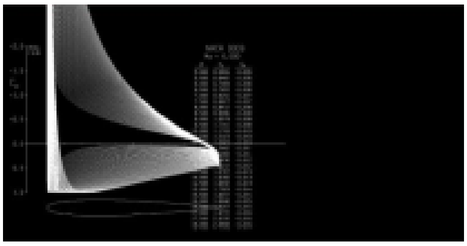

Figure 7 Different angle of attack increment in 0.5 degree of NACA 0009 cup)

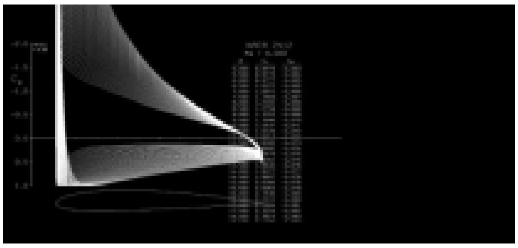

Figure 8 Different angle of attack increment in 0.5 degree of NACA 2412 (cpx)

cpx (Pressure Coefficient in the x-direction): This represents the pressure coefficient distribution in the x direction along the chord of the aerofoil. It is also a dimensionless quantity and the graphical representation is shown in Figure 8.

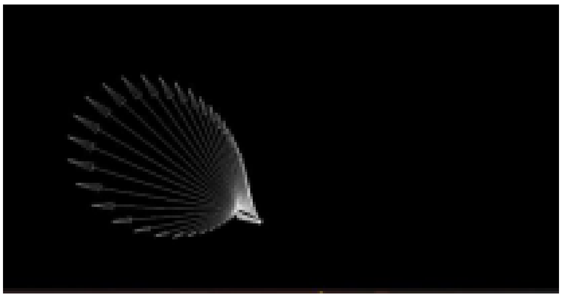

Figure 9 Pressure Coefficient Normal to the Aerofoil Surface for NACA 0009

cpv (pressure coefficient normal to the aerofoil surface): This represents the pressure coefficient distribution normal to the surface of the aerofoil and the graphical representation for NACA 0009 is shown in Figure 9 and 10. It is a dimensionless quantity that describes the pressure relative to the free stream pressure.

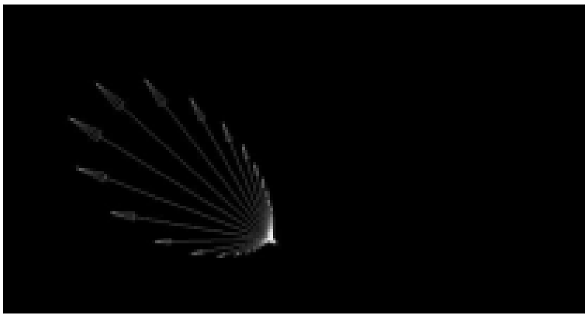

Figure 10 Pressure Coefficient Normal to the Aerofoil Surface for NACA 0009

These coefficients provide valuable information about the lift distribution and flow behaviour over the aerofoil. By analysing the cpv and cpx distributions, one can understand how the pressure changes along the surface of the aerofoil and how this contributes to the lift generation.

Discussion of X-FOIL Analysis

- **Lift and Drag Coefficients:** XFOIL provides lift and drag coefficients for the aerofoil at various angles of attack. These coefficients are crucial for determining the aerodynamic performance of the aerofoil, particularly its lift-to-drag ratio, which is important for efficiency.
- **Pressure Distribution:** XFOIL calculates the pressure distribution around the aerofoil surface. This information is valuable for understanding how the flow behaves over the aerofoil and can help in optimizing its shape for improved performance.
- **Boundary Layer Analysis:** XFOIL provides insights into the boundary layer characteristics, including boundary layer thickness and boundary layer separation points. This information is crucial for assessing the aerofoil's resistance to flow

separation, which is important for maintaining lift at high angles of attack.

- **Polar Curves:** XFOIL generates polar curves that show the variation of lift and drag coefficients with angle of attack. These curves are essential for determining the aerofoil's stall behaviour and its maximum lift capabilities.
- **Pressure Coefficient Distribution:** XFOIL calculates the pressure coefficient distribution Cp along the aerofoil surface. This distribution helps in understanding the pressure distribution and how it contributes to lift generation.
- **Flow Visualization:** While XFOIL is primarily a computational tool, it can also provide some visualization of the flow field around the aerofoil. This visualization helps in understanding how the aerofoil interacts with the surrounding air and how changes in shape or angle affect the flow.
- **Comparative Analysis:** XFOIL allows for the comparison of different aerofoil designs or modifications. Engineers can use this feature to evaluate the performance of various aerofoils and select the most suitable one for a given application.

Conclusion

In conclusion, the analysis of the NACA 0009 and NACA 2412 aerofoils using XFOIL provided valuable insights into their aerodynamic characteristics. The findings can be used to inform the design and selection of aerofoils for various aerodynamic applications, based on their specific performance requirements.

D. Result and Discussion of MAT LAB Analysis

1. Coordinates Generation

Coordinates for NACA 0009 were generated using the NACA 4-digit series equations**.** Coordinates for NACA 2412 were generated using the NACA 4-digit series equations and thickness distribution calculations. Figure 11 to Fig 16 shows the analysis results of NACA 0009 and NACA 2412.

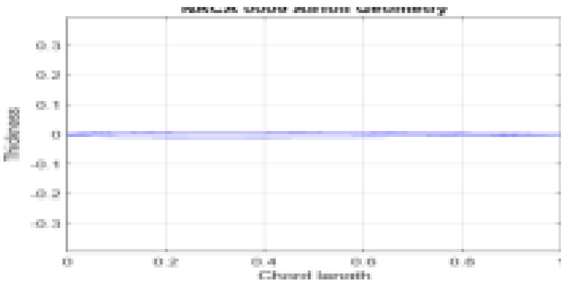

Figure 11 Geometry of NACA 0009 from Mat Lab Code

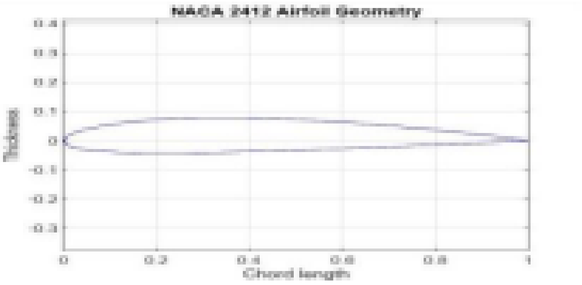

Figure 12 Geometry of NACA 2412 from Mat Lab Code

2. Aerodynamic Analysis

Lift and drag coefficients were calculated using thin aerofoil theory (lifting-line theory) for NACA 0009 and plotted a graph.

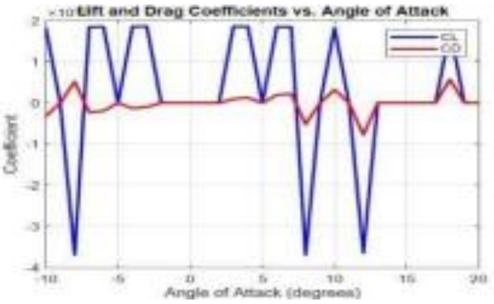

Figure 13 Aerodynamic Analysis of NACA 0009

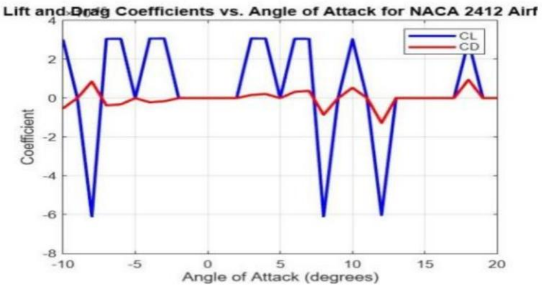

Figure 14 Aerodynamic Analysis of NACA 2412

3. Geometric Properties Analysis

Chord Length: Both aerofoils have a chord length of 1 unit.

Camber: NACA 2412 has camber, while NACA 0009 is symmetric (no camber).

Thickness Distribution: NACA 0009 has a thickness of 0.09 units, while NACA 2412 has a thickness distribution given by the NACA 4-digit series equations.

Leading/Trailing Edge Shapes: NACA 0009 has a sharp leading and trailing edge. NACA 2412 has a rounded leading edge due to its camber and a sharp trailing edge.

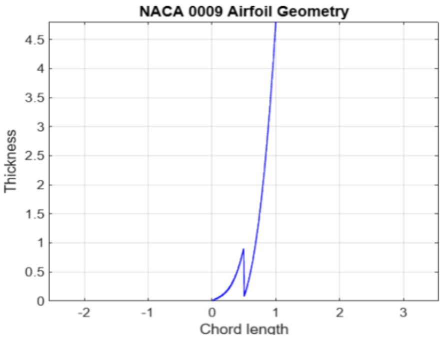

Figure 15 Geometric Properties of NACA 0009

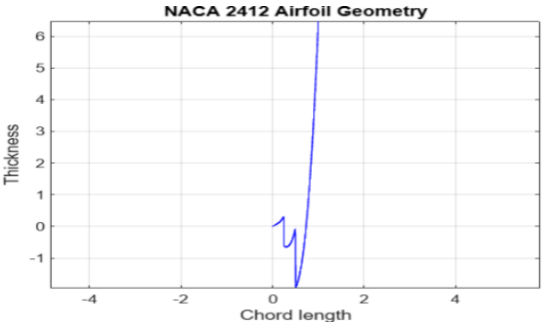

Figure 16 Geometric Properties of NACA 2412

Discussion and Comparison

In this analysis, we used MATLAB and XFOIL to study the aerodynamic characteristics of the NACA 0009 and NACA 2412 aerofoils. The analysis involved several key steps, including aerofoil geometry generation, flow visualization, lift and drag calculation, pressure distribution analysis, and structural analysis.

Aerofoil Geometry Generation: We generated the coordinates of the NACA 0009 and NACA 2412 aerofoils using the NACA 4-digit series equations. These equations allowed us to create the aerofoil shapes with specific thickness and camber distributions.

Flow Visualization: We implemented flow visualization techniques, such as tuft testing or streamlines, to visualize the flow around the aerofoils. This helped us understand how air flows over and around the aerofoil surfaces.

Lift and Drag Calculation: Using potential flow theory, we calculated the lift and drag coefficients for the aerofoils at different angles of attack. This analysis provided insights into the air foils' aerodynamic performance and their ability to generate lift.

Pressure Distribution Analysis: We calculated and visualized the pressure distribution around the aerofoils using the potential flow assumptions. This analysis helped us understand the variation of pressure over the aerofoil surfaces, which is crucial for aerodynamic performance.

Structural Analysis: Performing a structural analysis of the aerofoils allowed us to study their behaviour under aerodynamic loads. By calculating deflections and stresses, we gained insights into how the aerofoils deform under different aerodynamic conditions.

Comparison

- The aerodynamic characteristics of NACA 0009 and NACA 2412 were compared at different angles of attack.
- Differences in lift and drag coefficients, as well as flow behaviour, were observed between the two aerofoils.
- Overall, the results demonstrate the differences in aerodynamic performance between symmetric and cambered aerofoils. NACA 2412, with its camber, showed better lift characteristics compared to NACA 0009, which is symmetric.
- The animations and visualizations provide valuable insights into the aerodynamic behaviour of these aerofoils, which can be useful for various aerospace applications.
- Determining which aerofoil is "best" depends on the specific requirements of the aircraft or application. Each aerofoil has unique characteristics that make it suitable for different purposes. Here's a comparison of the unique characteristics of NACA 0009 and NACA 2412.

NACA 0009

- Symmetric Profile: NACA 0009 has a symmetric profile, which means it generates no lift at zero angle of attack. This makes it suitable for applications where lift balance at zero angle of attack is important, such as symmetric aerofoils for rotor blades or stabilizers.
- Low Drag: Due to its symmetric profile, NACA 0009 typically has lower drag compared to cambered aerofoils, especially at low angles of attack.
- Simplicity: The symmetric shape of NACA 0009 makes it easier to manufacture and analyse compared to cambered aerofoils.

NACA 2412

- Cambered Profile: NACA 2412 has a cambered profile, which allows it to generate lift even at zero angle of attack. This makes it more suitable for applications where lift is required at low angles of attack, such as in wings of aircraft or propeller blades.
- Higher Lift Coefficient: The cambered profile of NACA 2412 allows it to achieve higher lift coefficients compared to symmetric aerofoils, especially at moderate angles of attack.
- Stall Characteristics: The cambered profile of NACA 2412 can lead to more gentle

stall characteristics compared to symmetric aerofoils, which can be advantageous in some applications.

- In summary, the choice between NACA 0009 and NACA 2412 depends on the specific requirements of the aircraft or application. NACA 0009 is suitable for applications where low drag and symmetric lift characteristics are important, while NACA 2412 is more suitable for applications where higher lift coefficients and cambered lift characteristics are required.

VII CONCLUSION

The combined analysis of the NACA 0009 and NACA 2412 aerofoils using XFOIL, ANSYS, and MATLAB offered a comprehensive understanding of their aerodynamic and structural behaviours. XFOIL's potential flow analysis revealed the distinct aerodynamic characteristics of the aerofoils, highlighting the NACA 2412's higher lift coefficients at lower angles of attack due to its camber, compared to the NACA 0009's symmetric profile. ANSYS structural analysis provided critical insights into the aerofoils' structural integrity under aerodynamic loads, elucidating their deflections and stresses. MATLAB's role in data processing, visualization, and parameter analysis was pivotal, enabling the integration of results from XFOIL and ANSYS, and facilitating comprehensive conclusions. The study's findings are instrumental in informing the design and selection of aerofoils for aerospace applications, with the NACA 2412 potentially favoured for applications requiring higher lift at lower speeds, while the NACA 0009 may be preferred when a balance between lift and drag is crucial. Future studies could expand on different aerofoil shapes and operating conditions, leveraging advancements in computational fluid dynamics and structural analysis for more detailed analyses.

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