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Design And Analysis of Aircraft Wings by Computational Fluid Dynamics

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Abstract : This study explores the utilization of NACA airfoil shapes in aircraft wing design for training purposes, focusing on three specific profiles: NACA 2408, 2412, and 2415. These profiles were selected for their favorable aerodynamic characteristics. Detailed geometric designs of the airfoils, including chord length, ribs, spars, stringers, and skin, were created in SolidWorks, adhering to standard design practices. The structural aspects of the wings were addressed using Carbon Fiber composite materials, chosen for their exceptional strength-to-weight ratio, ideal for aerospace applications. Aerodynamic performance, including lift, drag, and static pressure, was analyzed using Computational Fluid Dynamics (CFD) simulations. Additionally, the structural integrity of the wings under lift and drag conditions was examined to ensure compliance with safety and performance standards. The results of this study provide valuable insights into the application of computational tools in aircraft wing design and analysis, contributing to advancements in aerospace engineering. According to the CFD research, the NACA 2412 airfoil exhibits the highest lift force, compared to the NACA 2408 and NACA 2415 airfoils by 18.34% and 2.27%, respectively. In terms of drag force, the NACA 2412 airfoil also performs best with the lowest drag , which is 27.77% lower than the NACA 2408 and 45.5% lower than the NACA 2415. Thus, considering both high lift and low drag, the NACA 2412 airfoil is the optimal choice for aircraft wing design. The superior performance of the NACA 2412 airfoil makes it the most suitable selection for achieving efficient flight dynamics.

***Index Terms* - Airfoil, Aircraft Wing Design, Computational Fluid Dynamics (CFD).**

I. INTRODUCTION

Aircraft wings are fundamental components of an aircraft's structure, providing lift and stability during flight. They are typically positioned horizontally across the fuselage and are designed to generate lift by deflecting air downward as the aircraft moves forward. The shape, size, and configuration of wings vary depending on the type of aircraft and its intended purpose. One of the primary functions of aircraft wings is to generate lift, allowing the aircraft to overcome gravity and become airborne. This lift is created through the interaction of the wing's shape, angle of attack, and the airflow over its surface. Wings also play a crucial role in providing stability and control during flight. By adjusting the ailerons, elevators, and flaps located on the wings, pilots can control the aircraft's roll, pitch, and yaw movements. Efficient wing design is essential for minimizing drag and maximizing fuel efficiency. Modern aircraft wings are carefully engineered to reduce drag through features such as winglets, wingtip devices, and smooth aerodynamic shapes. An airfoil is the cross-sectional shape of a wing or blade, designed to produce lift when moving through air. It is characterized by its curvature or camber and the angle of attack at which it meets the airflow. Airfoils can be symmetrical or asymmetrical, depending on their shape. Symmetrical airfoils have identical upper and lower surface shapes, resulting in zero camber and are commonly used in aerobatic and high-speed aircraft. Asymmetrical airfoils, with different upper and lower surface shapes, produce camber and lift even at zero angle of attack and are prevalent in most general aviation and commercial aircraft. The objective of this investigation is to analyze various NACA airfoil shapes, design airfoil wings through theoretical calculations, create models in 3D software, and analyze these models in Computational Fluid Dynamics to understand airfoil performance. This study reveals that at a 15-degree angle of attack, the NACA 2415 airfoil has 2.5% higher drag and 2.5% lower lift compared to the NACA 2412 airfoil. For NACA 4412 airfoils, titanium alloy is preferred for subsonic wings due to its superior strength-to-weight ratio, despite having higher stress, deformation, and lower strain compared to aluminum alloy. In NACA 23015 airfoil studies, a CFRP skin provides a 2.37% weight reduction, 51% less deformation, and 85% lower von-Mises stress than a titanium skin, showcasing the benefits of CFRP composites. Asymmetric and semisymmetric airfoils like NACA 2408 and NACA 2415 deliver up to 114% higher lift and 69% lower drag compared to the symmetric NACA 0012, though the NACA 0012 is better for low-speed flexibility. The aim is to compare lift, drag, and static pressure for different NACA airfoil shapes and to determine which NACA airfoil shape offers the most efficiency and sustainability in aircraft wing construction.

II. EXPERIMENTAL PROCEDURE

The experimental procedure began with the selection of various NACA airfoil shapes, including NACA 2408, NACA 2412, and NACA 2415. Theoretical calculations were performed to determine the geometric properties of these airfoils, and 3D models were created using CAD software such as SolidWorks, ensuring consistent scaling. Materials such as aluminum alloy, and carbon fiber reinforced polymer (CFRP) were selected for wing construction, with their properties documented. The 3D models were imported into a CFD software like SOLIDWORKS and a computational domain with appropriate boundary conditions was set up to simulate airflow over the airfoils. The fluid properties, including air density and viscosity, were defined along with flow conditions like velocity and angle of attack. Computational meshes were generated for each airfoil, refined around critical areas, and mesh independence studies were conducted to ensure result accuracy. CFD simulations were run for each airfoil at an constant angles of attack monitoring convergence criteria to ensure reliable results, and recording lift, drag, and static pressure values. The CFD results of different NACA airfoils were compared. All procedures, including theoretical calculations, 3D modeling steps, CFD setup, and simulation parameters, were documented, and observations and adjustments were recorded. The data was analyzed to determine which NACA airfoil shape offered the best performance in terms of lift, drag, and efficiency, leading to conclusions on the efficiency and sustainability of each airfoil shape for aircraft wing construction.

2.1 Airfoil Components

- Leading edge: The forward point of the airfoil.
- Trailing edge: The rearward point of the airfoil.
- Chord line: The straight line connecting the leading and trailing edges.
- Chord (c): Distance from leading to trailing edge along the chord line.

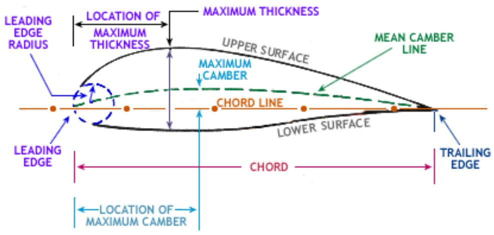
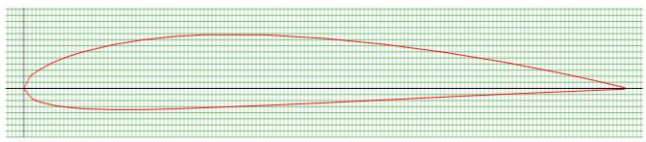
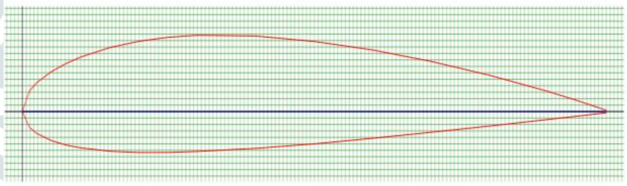
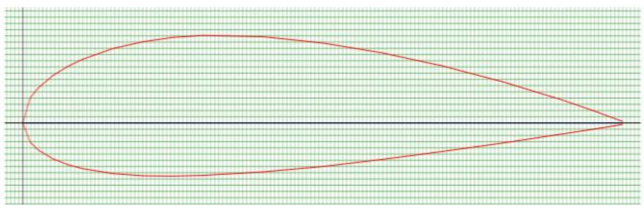


Fig 2.1 Airfoil Components

2.2 NACA Airfoil Co-ordinates Graph

Airfoil	Airfoil Co-ordinates Graph
NACA 2408	
NACA 2412	
NACA 2415	

2.3 Parts of Aircraft wings

2.3.1 Part 1: Ribs:

They are spaced at regular intervals along the wing span, typically 12-24 inches apart. Ribs are attached to the spar and stringers, and provide a nailing surface for the skin. They help to maintain the wing's shape and prevent it from deforming under load

Airfoil	Length (mm)	Thickness(mm)	N.o of Items
NACA 2408	1500	10	10
NACA 2412	1500	10	10
NACA 2415	1500	10	10

Table 2.3.1 Ribs Dimension details

2.3.2 Part 2: Spar:

It is designed to carry the majority of the wing's structural load, including lift, drag, and weight. It is designed to be resistant to bending, torsion, and shear loads. The spar also provides a mounting point for the wing's control surfaces and landing gear

Airfoil	Length (mm)	Width (mm)	Thickness(mm)	N.o of Items
NACA 2408	4500	60	60	3
NACA 2412	4500	60	60	3
NACA 2415	4500	60	60	3

Table 2.3.2 Spar Dimension details

2.3.3 Part 3: Stringers:

Stringers are typically smaller and lighter than the spar, but still play a critical role in the wing's structure. They are designed to distribute loads from the skin to the ribs and spar, and help to maintain the wing's shape. Stringers are usually made of the same materials as the spar and ribs.

Airfoil	Length (mm)	Width (mm)	Thickness(mm)	N.o of Items
NACA 2408	4500	30	15	4
NACA 2412	4500	30	15	4
NACA 2415	4500	30	15	4

Table 2.3.3 Stringers Dimension details

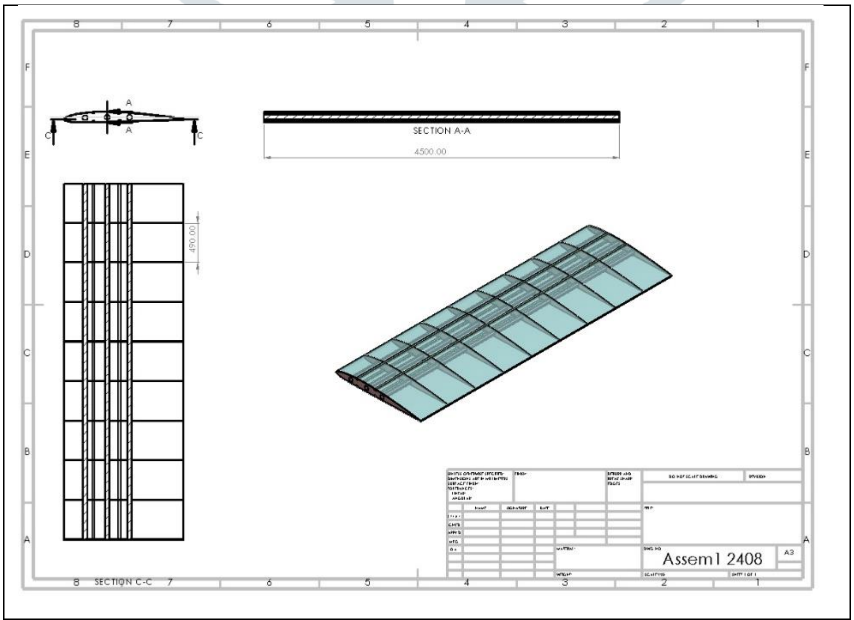
2.3.4 Part 4: Skin:

The skin is the outermost layer of the wing, and is designed to be smooth and aerodynamically efficient. The skin is attached to the ribs, spar, and stringers using rivets, bolts, or adhesive bonding. It is designed to withstand aerodynamic forces, including lift, drag, and shear loads.

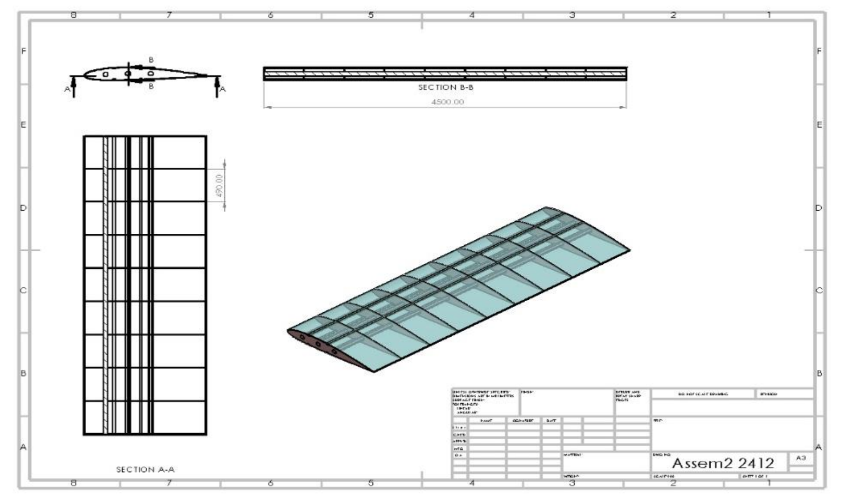
Airfoil	Length (mm)	Width (mm)	Thickness(mm)	N.o of Items
NACA 2408	4500	1500	08	1
NACA 2412	4500	1500	12	1
NACA 2415	4500	1500	15	1

Table 2.3.4 Skin Dimension details

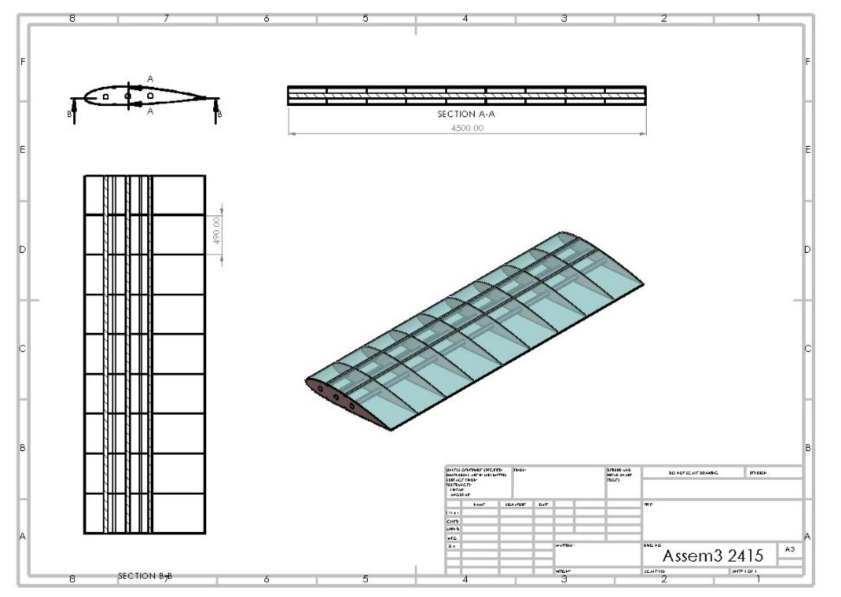
2.4 Modeling



Assembly of NACA 2408 Model



Assembly of NACA 2412 Model



Assembly of NACA 2415 Model

2.5 Comparisons of NACA 2408, 2412 & 2415 Models

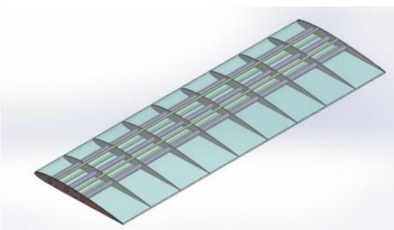


Fig 2.5.1 NACA 2408 Model

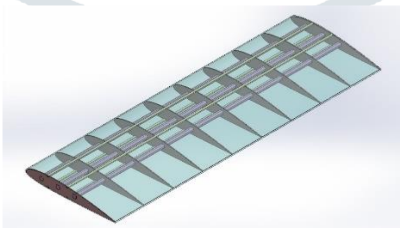


Fig 2.5.2 NACA 2412 Model

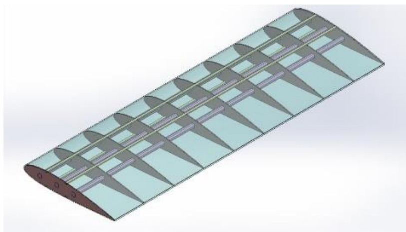


Fig 2.5.3 NACA 2415 Model

2.6 Material Selection

- Aluminum Alloy(AA 2024):- Part 1. Rib, Part 2. Spar & Part 3. Stringers.
- Carbon Fiber:- Part 4. Skin.

2.6.1 Reasons:

Aluminum alloys provide high strength-to-weight ratios for ribs, spars, and stringers, ensuring structural integrity without adding excessive weight. Carbon Fiber skin offers excellent tensile strength, enhancing the wing's ability to withstand aerodynamic forces. Aluminium alloys resist corrosion and fatigue, making them durable for critical structural components like ribs, spars, and stringers. Carbon Fiber skin resists impact damage and cracking, providing a robust outer layer that protects the internal structure. The hybrid structure minimizes corrosion and damage, reducing maintenance needs and enhancing the overall lifespan of the wing.

2.6.2 Properties of Aluminum Alloy (AA-2024):

Property	Value
Density (r)	2800 Kg/m3
Ultimate Strength (SuT)	572 MPa
Modulus of Elasticity (E)	71.7 GPa
Shear Modulus (G)	26.9 GPa
Poisson's ratio (n)	0.33

Table 2.6.2 Properties of Aluminum Alloy (AA-2024)

2.6.3 Properties of Carbon Fiber:

Property	Value
Density	1800 kg/m3
Young's Modulus X Direction	3.95E+11 Pa
Young's Modulus Y Direction	6E+09 Pa
Young's Modulus Z Direction	6E+09 Pa
Poisson's ratio XY	0.2
Poisson's ratio YZ	0.4
Poisson's ratio XZ	0.2
Shear Modulus XY	8E+09 Pa
Shear Modulus YZ	2.1429E+09 Pa
Shear Modulus XZ	8E+09 Pa

Table 2.6.3 Properties of Carbon Fiber

III. Results and discussion

In the computational fluid dynamics (CFD) analysis of the aircraft wing, the boundary conditions are set as follows: The fluid under consideration is air, with an external flow type. The flow velocity is maintained at 35 meters per second, and the operating pressure is set at 101325 Pascals. The fluid density is 1.22 kilograms per cubic meter. The Reynolds number for this analysis is set at 10^6, which indicates the flow regime. The angle of attack is set to 0 degrees, representing a horizontal airflow relative to the wing profile. These conditions provide a comprehensive framework for simulating the aerodynamic characteristics of the wing under standard atmospheric conditions.

3.1 Domain Condition for CFD Analysis

- Type of Fluid- Air
- Flow of Fluid- External
- Velocity of Flow- 35m/s
- Pressure- operating- 101325 Pa
- Fluid Density- 1.22 Kg/m^3
- Reynolds Number- 10^6
- Angle of Attack- 0º

3.2 Analysis NACA 2408

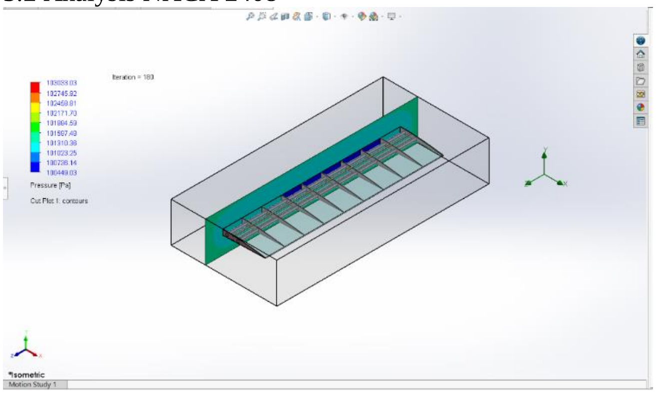


Fig 3.2.1 NACA 2408 Cut Plot

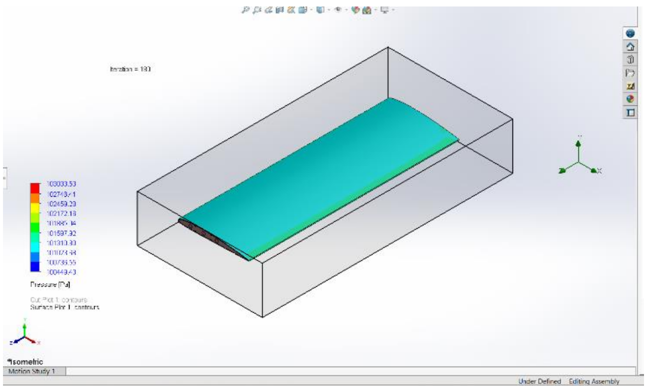


Fig 3.2.2 NACA 2408 Surface Plot

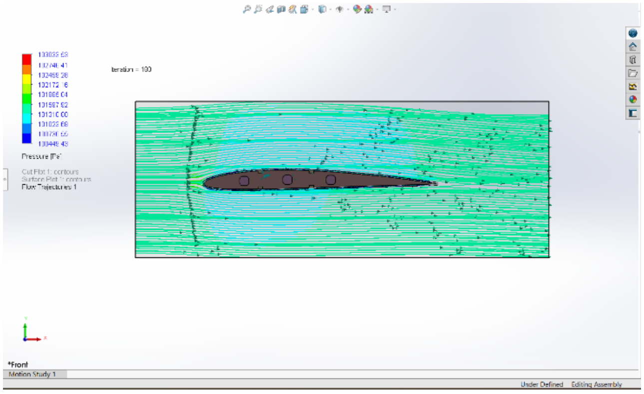


Fig 3.2.3 NACA 2408 Flow Trajectories

3.3 Analysis NACA 2412

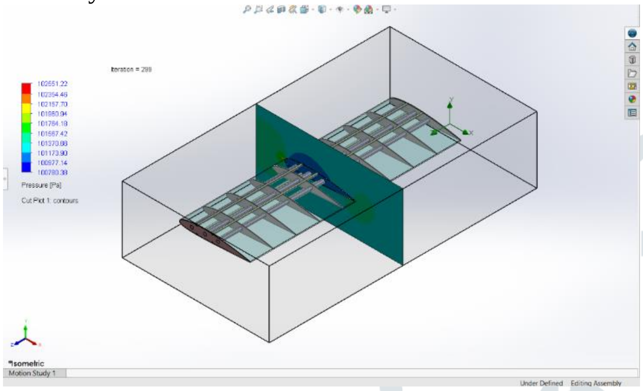


Fig 3.3.1 NACA 2412 Cut Plot

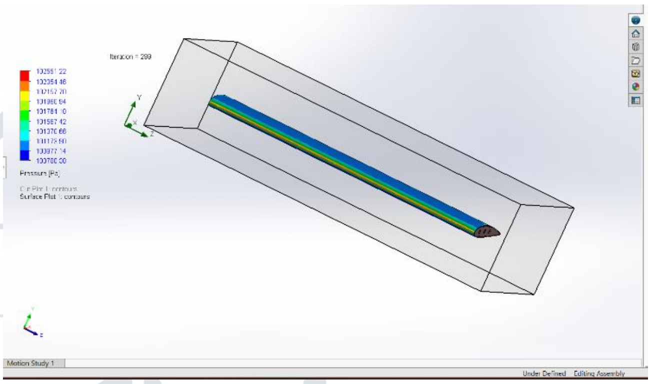


Fig 3.3.2 NACA 2412 Surface Plot

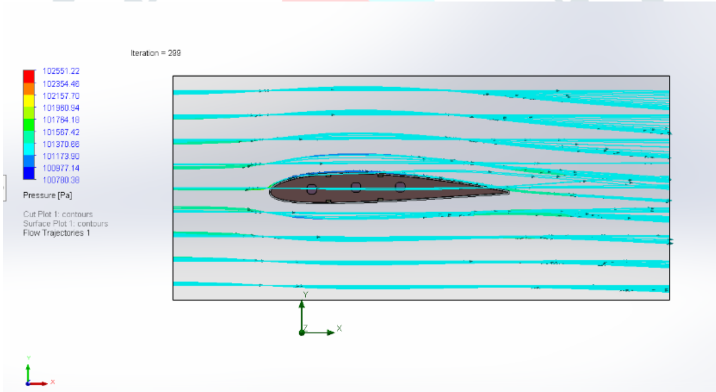


Fig 3.3.3 NACA 2412 Flow Trajectories

3.4 Analysis NACA 2415

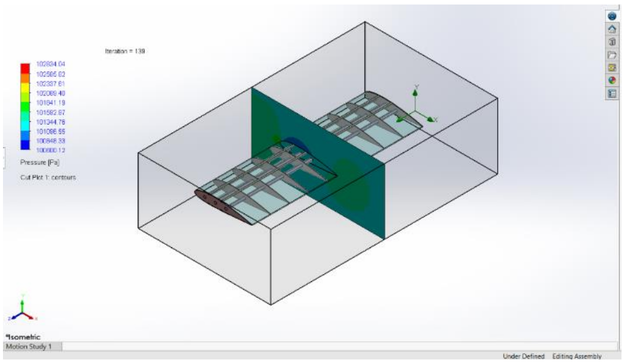


Fig 3.4.1 NACA 2415 Cut Plot

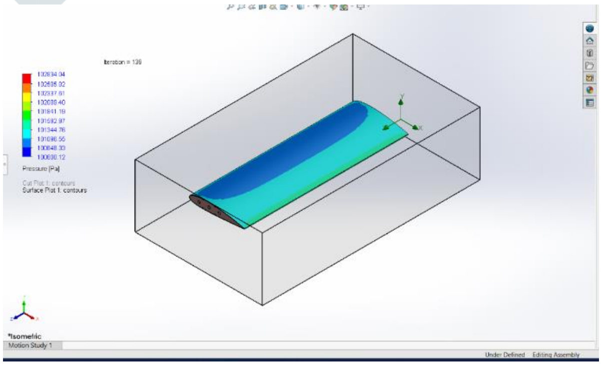


Fig 3.4.2 NACA 2415 Surface Plot

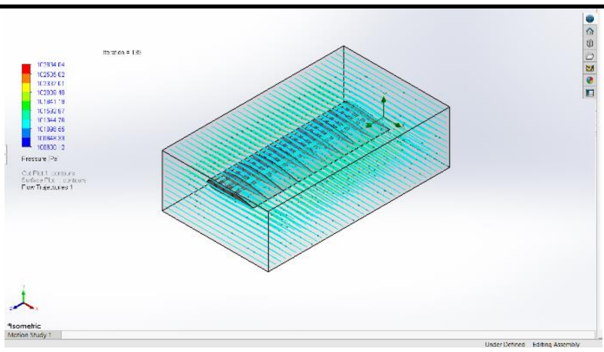


Fig 3.4.3 NACA 2415 Flow Trajectories

3.5 Theoretical Calculation

- Lift Force (L_F)

  $L_F = 0.5*\rho*v^2*c_f*S$

- Drag Force (D_F)

  $D_F = 0.5*\rho*v^2*c_d*S$

were,

S – Surface Area of Wing
ρ – Density of Air
v – Velocity of Aircraft wing
C_f - Co-efficient of Lift
C_d - Co-efficient of Drag

Airfoil Shape	NACA 2408	NACA 2412	NACA 2415
Mass of Aircraft Wing (Kg)	200	208	215
Surface Area of Wing (m^2)	34.72	36.28	37.40
Velocity of Aircraft Wing (m/s)	35	35	35
Density of Air (kg/m^3)	1.22	1.22	1.22
Co-efficient of Lift	0.284	0.322	0.305
Co-efficient of Drag	0.012	0.009	0.016

Table 3.5 Domain Data

3.6 Results and discussion

Airfoil Shapes	**Lift Force (N)**	**Drag Force (N)**	**Static Pressure (KPa)**	
			Max	**Min**
NACA 2408	7368.243	337.278	103.033	100.449
NACA 2412	8717.463	243.655	102.551	100.780
NACA 2415	8523.880	447.154	102.834	100.600

Table 3.6 Result and Discussion

The analysis of the aircraft wing utilizes three different NACA airfoil shapes: NACA 2408, NACA 2412, and NACA 2415. For the NACA 2408 profile, the mass of the wing is 200 kilograms, with a surface area of 34.72 square meters. The NACA 2412 wing has a mass of 208 kilograms and a surface area of 36.28 square meters. The NACA 2415 profile, the heaviest and largest, has a mass of 215 kilograms and a surface area of 37.40 square meters. Each wing operates at a constant velocity of 35 meters per second in an airstream with a density of 1.22 kilograms per cubic meter. The coefficients of lift for the NACA 2408, 2412, and 2415 profiles are 0.284, 0.322, and 0.305, respectively, while the coefficients of drag are 0.012, 0.009, and 0.016, respectively. These parameters are crucial for understanding the aerodynamic performance of each wing profile under similar flight conditions.

IV. Conclusion

- According to the CFD research, the NACA 2412 airfoil exhibits the highest lift force among the analysed airfoils, generating 8717.463 N. This performance is notably superior when compared to the NACA 2408 and NACA 2415 airfoils, with the NACA

2412 providing 18.34% more lift than the NACA 2408 and 2.27% more lift than the NACA 2415. The enhanced lift capability of the NACA 2412 airfoil makes it a strong candidate for applications where maximizing lift is critical, such as in aircraft wing design, where effective lift generation is paramount for efficient takeoff, cruising, and overall flight performance.

- In terms of drag force, the NACA 2412 airfoil also demonstrates superior performance, exhibiting the lowest drag force at 243.655 N. This drag force is significantly lower than that of the NACA 2408 and NACA 2415 airfoils, being 27.77% and 45.5% lower, respectively. The combination of high lift and low drag underscores the NACA 2412 airfoil as the optimal choice for aircraft wing design. This superior aerodynamic efficiency contributes to better fuel economy and overall flight dynamics, making the NACA 2412 the most suitable selection for achieving efficient and effective flight performance. Therefore, the NACA 2412 airfoil's ability to provide high lift while minimizing drag confirms its excellence in enhancing the aerodynamic efficiency of aircraft wings.

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