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Comparative Analysis of NACA Airfoil Series Performance using Computational Fluid Dynamics (CFD)

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Abstract:

This research paper explores how Computational Fluid Dynamics (CFD) simulations can be used to analyze and improve designs for airfoils, the wing-shaped structures that generate lift. It focuses on NACA airfoils, a system categorized by numbers that define their aerodynamic properties. Using CFD, researchers can virtually test different NACA airfoils to see how well they generate lift, create drag, and behave when airflow stalls (disrupts). The paper also examines how factors like thickness, curvature (camber), and angle of attack influence these performances. By understanding these factors, engineers can choose the ideal NACA airfoil for various applications, from airplane wings to wind turbine blades.

Keywords: NACA airfoils, CFD simulations, aerodynamic performance, lift, drag, stall, Reynolds number, airfoil series, boundary conditions, optimization, engineering applications

I. INTRODUCTION:

The development of Computational Fluid Dynamics (CFD) has revolutionized the field of aerodynamics. airfoils, the wing-shaped structures that generate lift, are crucial components in many engineering systems, impacting performance and efficiency in aircraft, wind turbines, and even automobiles. The NACA airfoil series, a cornerstone of aerodynamic research, offers a vast collection of designs identified by unique numerical codes.

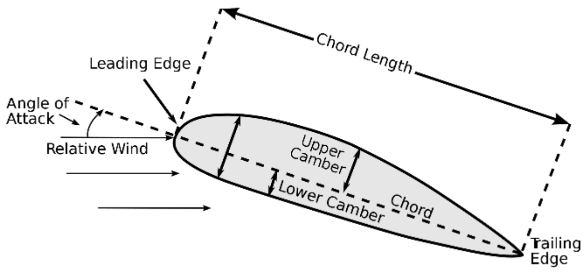


Figure 1 - Airfoil Diagram

The NACA airfoil series, created by the National Advisory Committee for Aeronautics (precursor to NASA), represents a structured method for designing airfoils. Each design has a unique numerical code that encodes its geometric properties like thickness and curvature. This systematic organization allows engineers to easily compare airfoils and choose the optimal one for their needs.

This review paper tackles the challenge of understanding how NACA airfoils from various categories perform. By combining existing research and CFD simulations, the paper offers a thorough analysis of the performance of different NACA designs. Unravelling the complexities of airflow over these airfoils is essential for maximizing aerodynamic efficiency and boosting the overall performance of engineering systems.

CFD analysis empowers researchers to delve into the numerous factors that influence airfoil performance, including lift, drag, and how the airfoil behaves when airflow stalls. It allows for systematic investigation of how thickness, curvature (camber), and angle of attack impact aerodynamics. By analyzing these factors, engineers can refine existing designs or create entirely new airfoil configurations optimized for specific applications.

This review paper bridges the gap between theory and practice in NACA airfoil use. While theoretical models offer valuable knowledge, CFD simulations provide a realistic picture of airflow dynamics and enable quantifiable analysis of performance. By combining theory with computational methods, this paper aims to provide actionable insights for engineers and researchers working on airfoil design and optimization.

In essence, this review serves as a comprehensive resource on CFD analysis of various NACA airfoil series. By explaining the aerodynamic characteristics of these airfoils, the paper facilitates informed decision-making in selecting and optimizing airfoil designs for diverse engineering applications. Through a systematic examination of airflow phenomena and performance metrics, this paper contributes to the advancement of both aerodynamic research and engineering practice.

II. TYPES OF AIRFOILS:

Airfoils, also known as aerofoils, come in various shapes and designs, each tailored for specific applications. Here are a few common types and their applications:

1. **Symmetrical Airfoils:** These airfoils have identical upper and lower surfaces, generating equal lift at zero angle of attack. They are often used in aircraft wings where aerobatic performance is desired, such as stunt planes and model aircraft.
2. **Asymmetrical (Cambered) Airfoils:** These airfoils have different upper and lower surfaces, creating lift even at zero angle of attack. They are commonly used in general aviation aircraft, commercial airliners, and military aircraft.
3. **High-Lift Airfoils:** These airfoils are designed to generate higher lift coefficients at low speeds, enabling shorter take-off and landing distances. They are often employed in aircraft such as cargo planes, short-haul regional jets, and commuter aircraft.
4. **Supercritical Airfoils:** Supercritical airfoils are designed to delay the onset of wave drag, making them suitable for high-speed aircraft like airliners and business jets where maintaining efficiency at transonic speeds is crucial.
5. **NACA Airfoils:** Developed by the National Advisory Committee for Aeronautics (NACA), these airfoils come in various series (e.g., NACA 4-digit, 5-digit) and were widely used in the design of early aircraft. They find applications in a broad range of aircraft types due to their versatility and well-understood aerodynamic characteristics.
6. **Natural Laminar Flow (NIF) Airfoils:** These airfoils are designed to maintain laminar airflow over a larger portion of the wing surface, reducing drag and improving fuel efficiency. They are commonly utilized in modern high-performance aircraft and sailplanes.

III. AIRFOIL SELECTION:

1. NACA 2412: The NACA 2412 airfoil is a classic design developed by the National Advisory Committee for Aeronautics (NACA). This workhorse profile is popular for its balanced performance in various applications, including aircraft wings and wind turbine blades. The unique numbering system of NACA airfoils reveals key features:

- 2: Maximum camber is 2% of the chord length (the wing's width). This moderate curvature creates lift without excessive drag.
- 4: Maximum camber location is at 40% of the chord length. This placement optimizes lift generation.

- 12: The airfoil is 12% thick compared to its chord length. This balance between thickness and curvature provides good structural integrity without sacrificing aerodynamic efficiency.

Applications: The NACA 2412's versatility makes it suitable for a wide range of uses:

- **Aircraft Wings:** This airfoil is a common choice for training aircraft and general aviation planes due to its predictable handling characteristics and good performance across various speeds.
- **Wind Turbine Blades:** The NACA 2412's ability to generate lift at lower wind speeds makes it a good option for some wind turbine designs.

In essence, the NACA 2412 airfoil's well-understood properties and balanced performance make it a reliable choice for many engineering applications.

2. NACA 64A212: The NACA 64A212 airfoil is a product of NACA's (now NASA's) ingenuity. This design strikes a balance between lift and drag, making it a versatile choice for various applications. The unique numbering system of NACA airfoils reveals key features:

- 64: This signifies it belongs to the 6-series, hinting at its general shape characteristics.
- A: This indicates a modification of the basic 6-series design, offering potentially improved performance.
- 2: The maximum camber (curvature for lift generation) is located at 20% of the chord length.
- 12: The airfoil is 12% thick compared to its chord length, providing a good balance between structural strength and aerodynamic efficiency.

Applications: The NACA 64A212's design philosophy centers around achieving a balance between lift and drag. Its moderate camber allows for good lift generation without creating excessive drag, a crucial factor for applications like:

- **Aircraft Wings:** This airfoil can be found in some aircraft wings, particularly those requiring a balance between performance and efficiency.
- **Helicopter Rotor Blades:** The ability to generate lift at varying angles makes it suitable for helicopter rotor blades that experience complex airflow patterns.

In essence, the NACA 64A212 airfoil's focus on balanced performance and its well-understood characteristics make it a reliable option for applications demanding both lift and efficiency.

3. NACA 0012: The NACA 0012 airfoil is a versatile design known for its simplicity and well-balanced properties. Developed by NACA (precursor to NASA), it excels in applications where both structural integrity and symmetrical behaviour are crucial. The unique numbering system of NACA airfoils reveals key features:

- 00: This indicates zero camber, meaning the upper and lower surfaces are mirror images, creating no lift at zero angle of attack.
- 12: The final digits represent a 12% thickness-to-chord ratio, offering good structural strength.

Applications: The NACA 0012's symmetrical design and thickness make it a popular choice for:

- **Aircraft Tail Surfaces:** Horizontal and vertical stabilizers often utilize this airfoil for their need for balanced lift and control at various angles.
- **Rotor Blades:** Helicopter rotor blades and some wind turbine blades benefit from the 0012's sturdiness while maintaining acceptable aerodynamic performance.

In essence, the NACA 0012 airfoil prioritizes balance and strength, making it a reliable choice for applications where symmetrical behaviour and structural integrity are essential.

4. NACA 23012: The NACA 23012 airfoil is another creation from the innovative minds at NACA. This design prioritizes a balance between symmetry and moderate thickness, making it suitable for various applications. The unique numbering system of NACA airfoils reveals key features:

- 23: This indicates it belongs to the 2-series, hinting at specific aerodynamic properties.
- 0: This signifies zero camber, meaning the upper and lower surfaces are identical, generating no lift at zero angle of attack.
- 12: The final digits represent a 12% thickness-to-chord ratio, providing a good balance between weight and structural strength.

Applications: Due to its symmetrical shape and moderate thickness, the NACA 23012 airfoil finds uses in:

- **Aircraft Wings:** Certain sections of aircraft wings, particularly those requiring balanced lift distribution, can benefit from this design.
- **Tail Surfaces:** Similar to the NACA 0012, horizontal and vertical stabilizers can leverage the 23012's symmetrical behaviour for control.
- **Marine Propellers:** In some propeller designs, the NACA 23012 can contribute to efficient performance due to its balanced properties.

In essence, the NACA 23012 airfoil's focus on symmetry and moderate thickness makes it a versatile choice for applications demanding balanced lift, structural integrity, and overall efficiency.

IV. AIRFOIL DESIGNS:

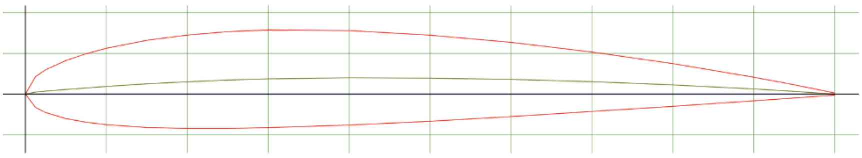


Figure 2 - NACA 2412

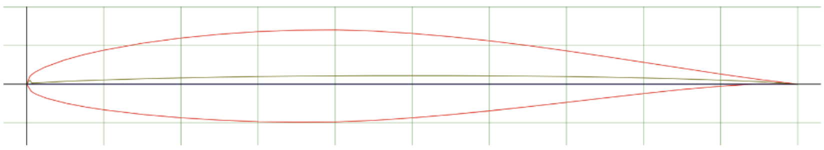


Figure 3 - NACA 64A212

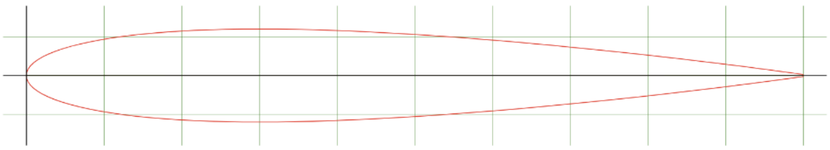


Figure 4 - NACA 0012

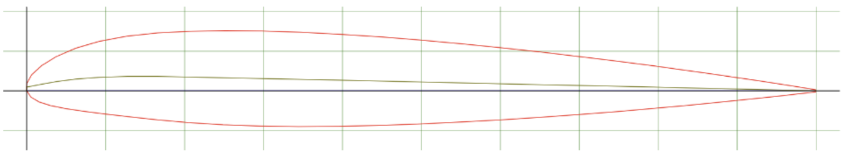


Figure 5 - NACA 23012

V. METHODOLOGY:

This review delves into the fascinating world of NACA airfoils through the lens of Computational Fluid Dynamics (CFD) analysis. Here's a breakdown of the key steps involved:

1. **Literature Review:** The journey begins with a comprehensive literature review. Researchers meticulously gather relevant research articles, conference papers, and technical reports that explore CFD analysis of

NACA airfoils. The focus here is to identify studies that offer in-depth CFD simulations and analyses of various NACA airfoils across diverse flow conditions.

2. **Selection Criteria:** Not all studies are created equal. The selection criteria for inclusion in this review are strict, prioritizing studies that:

   - Showcase detailed CFD simulations, providing valuable insights into airflow behaviour.
   - Discuss the aerodynamic performance of NACA airfoils, detailing their lift, drag, and stall characteristics.
   - Compare different airfoil designs, highlighting their strengths and weaknesses under varying conditions.

3. **Data Extraction:** Once the most relevant studies are identified, researchers meticulously extract crucial data. This data serves as the foundation for the comparative analysis and includes:

   - **Airfoil geometries:** The precise shapes of the airfoils being studied.
   - **CFD setup parameters:** The nitty-gritty details of how the CFD simulations were configured, including mesh type and density, boundary conditions, and turbulence models.
   - **Simulation results:** The gold mine of the analysis - the data on lift, drag, stall characteristics, and other aerodynamic performance metrics obtained from the CFD simulations.
   - **Conclusions:** The key takeaways and insights presented in the original studies.

4. **Comparative Analysis:** With the extracted data in hand, researchers embark on a comparative analysis. This analysis is like piecing together a puzzle, identifying trends and patterns in the CFD results. It sheds light on the strengths and weaknesses of each NACA airfoil series under different flow conditions.

5. **Discussion:** Building upon the comparative analysis, a detailed discussion interprets the findings. This discussion delves into the aerodynamic characteristics of various NACA airfoil series, providing a deeper understanding of their behaviour. It also includes a critical evaluation of the CFD methodologies used in the selected studies, exploring their implications for airfoil design and optimization.

6. **Conclusions And Recommendations:** The review culminates with a summary of the key findings from the comparative analysis. It explores the implications of these findings for future research and engineering practices in the field of airfoil design. Additionally, recommendations are provided based on the review's insights, outlining ways to improve CFD analysis of NACA airfoils and charting a course for future research endeavours.

VI. PROBLEM STATEMENT:

1. **The Crucial Role Of Airfoils:** The aerodynamic performance of airfoils is paramount for the success of various engineering marvels, from soaring aircraft to wind turbine giants. The NACA airfoil series, distinguished by their unique codes, stands as a cornerstone in airfoil design and aerodynamics research. However, despite extensive research, a comprehensive CFD analysis of these airfoils remains elusive.

2. **The Need for a Comparative Analysis:** Current literature offers valuable knowledge on the individual behaviour of NACA airfoils. Yet, a systematic comparison using CFD simulations is missing. This comparison is vital to understand the strengths and limitations of each design, ultimately guiding the selection and optimization of airfoils for specific applications.

3. **The Power of CFD:** Theoretical models and experiments have undoubtedly shaped our understanding of airfoil aerodynamics. However, CFD simulations offer an unparalleled tool for detailed numerical analysis of airflow over complex geometries like airfoils. While CFD applications exist for NACA airfoils, they are often isolated studies focusing on specific designs or conditions.

4. **This Review Paper's Focus:** This research paper tackles the lack of a comprehensive and systematic review of CFD analysis on various NACA airfoil series. By combining existing research with a

comparative analysis of CFD results, this paper aims to bridge the knowledge gap. The goal is to provide a thorough understanding of the aerodynamic performance of NACA airfoils across diverse operating conditions.

5. **The Expected Impact:** This review paper aspires to contribute to advancements in both aerodynamic research and engineering practices. It will achieve this by:

- Unveiling the relative performance of different NACA airfoil series.
- Informing the selection and optimization of airfoils for various applications.
- Highlighting areas for future research and development, particularly in applying CFD techniques to analyze NACA airfoils.

VII. BOUNDARY CONDITIONS:

In the realm of Computational Fluid Dynamics (CFD), boundary conditions play a critical role. These are essentially instructions applied to the edges of the computational domain, a virtual space where fluid flow is simulated. They dictate how the fluid interacts with these boundaries, influencing the behaviour of the entire flow within the domain. By setting appropriate boundary conditions, researchers can ensure the accuracy of their CFD simulations. Assume Mass = 10 kg, Weight = 100 N, Chord length = 1 meter.

Table 1 - Boundary Conditions

S.No.	Boundary Conditions	Value/On/Off
1	Pressure	101325 N/m^2
2	Density	1.225 Kg/m^3
3	Temperature	288 K
4	Viscous model	k-omega
6	Air inlet velocity	50 m/sec

VIII. MESHING:

These figures establish the baseline mesh configuration for all airfoils analyzed in the paper. It visually depicts an airfoil with its corresponding gridlines, serving as a reference for interpreting similar presentations in subsequent figures.

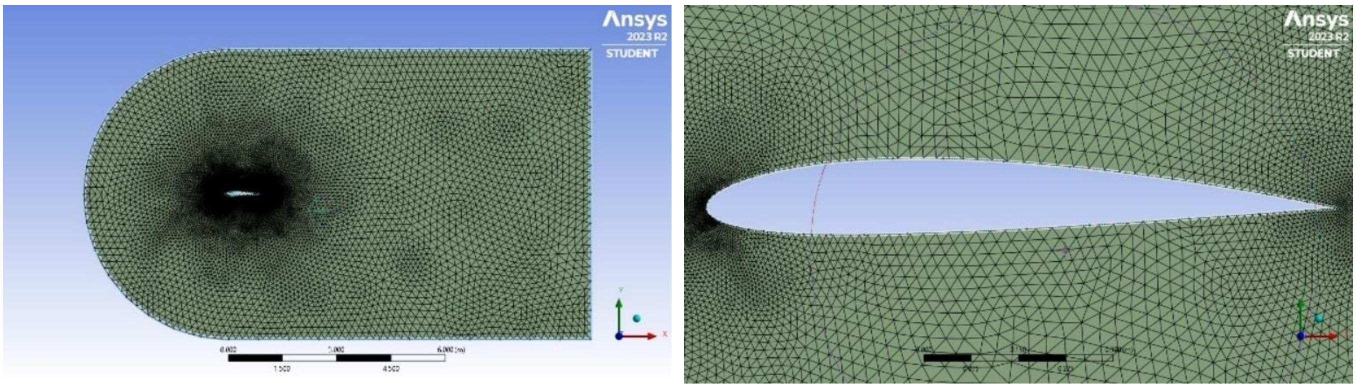


Figure 6 - Meshing of NACA 2412 (a) Complete Figure (b) Zoomed in on Airfoil

IX. RESULT:

Table 2 - NACA 2412

S.No.	AoA	Lift Force	Drag Force	Lift/Drag	Drag/Lift	Thrust T_R

1	0	50.1997	16.5499	3.033232829	0.329681253	32.968125308
2	5	322.6810	28.9316	11.153237291	0.089660067	8.966006675
3	10	621.6520	49.6386	12.523560294	0.079849498	7.984949779
4	15	897.6300	73.3875	12.231374553	0.081756960	8.175695999

Table 3 - NACA 64A212

S.No.	AoA	Lift Force	Drag Force	Lift/Drag	Drag/Lift	Thrust T_R
1	0	96.2663	15.3088	6.288298234	0.159025536	15.902553645
2	5	314.7820	27.2838	11.537322514	0.086675223	8.667522285
3	10	583.4420	46.3422	12.589864098	0.079428975	7.942897495
4	15	867.8560	71.1163	12.203334538	0.081944816	8.194481573

Table 4 - NACA 0012

S.No.	AoA	Lift Force	Drag Force	Lift/Drag	Drag/Lift	Thrust T_R
1	0	-36.7554	14.7758	-2.487540438	-0.402003515	-40.200351513
2	5	208.8620	22.3638	9.339289387	0.107074528	10.707452768
3	10	498.0100	40.1510	12.403427063	0.080622879	8.062287906
4	15	785.5360	64.0969	12.255444491	0.081596388	8.159638769

Table 5 - NACA 23012

S.No.	AoA	Lift Force	Drag Force	Lift/Drag	Drag/Lift	Thrust T_R
1	0	43.2400	15.1569	2.852826106	0.350529602	35.052960222
2	5	214.0100	23.3463	9.166763042	0.109089762	10.908976216
3	10	517.6970	42.3309	12.229765963	0.081767714	8.176771355
4	15	791.2200	65.6741	12.047671761	0.083003589	8.300358939

X. COMPUTATIONAL FLOW ANALYSIS:

1. NACA 2412

i. Pressure Distribution

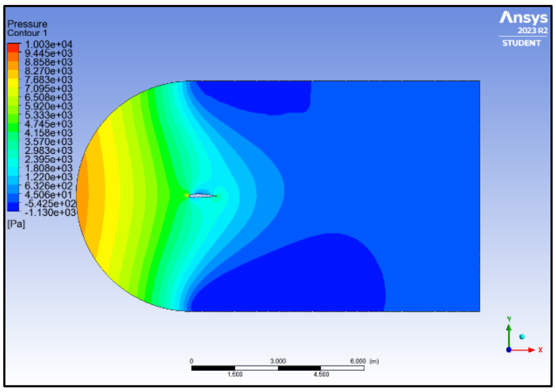


Figure 7 - AoA = 0

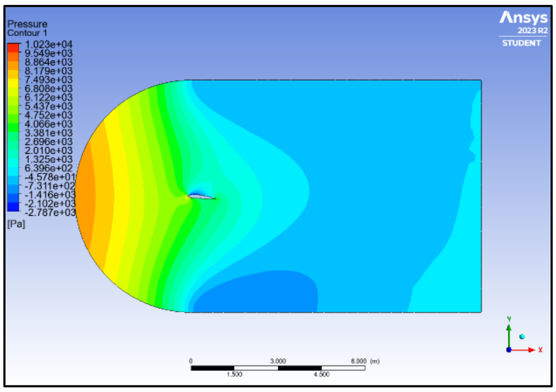


Figure 8 - AoA = 5

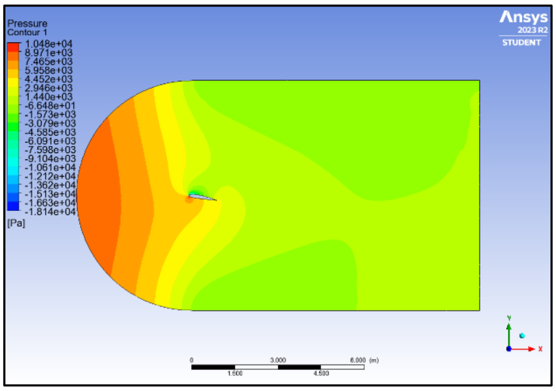


Figure 9 - AoA = 10

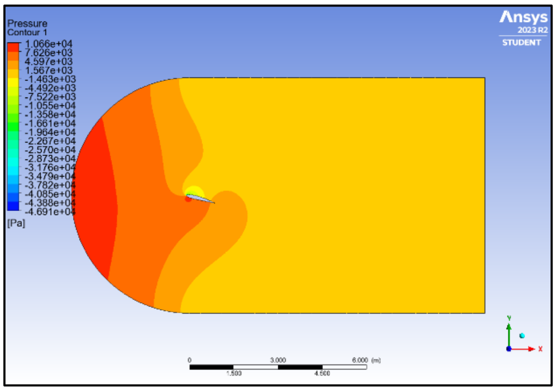


Figure 10 - AoA = 15

ii. Velocity Distribution

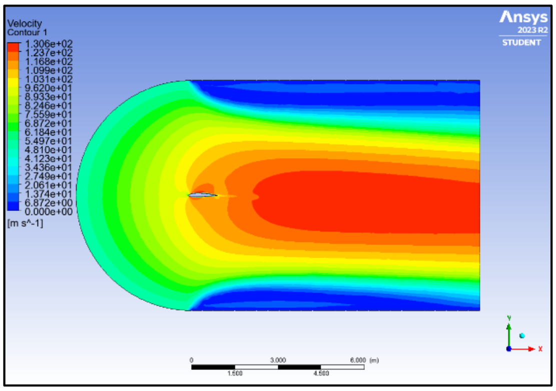


Figure 11 - AoA = 0

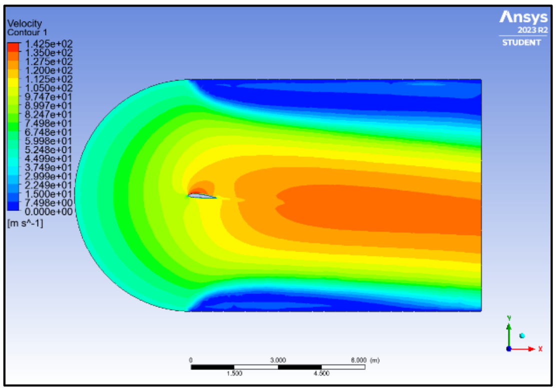


Figure 12 - AoA = 5

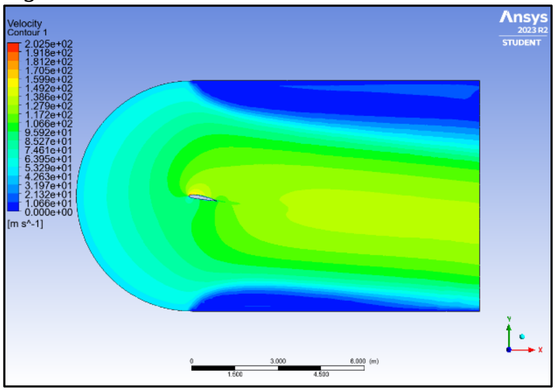


Figure 13 - AoA = 10

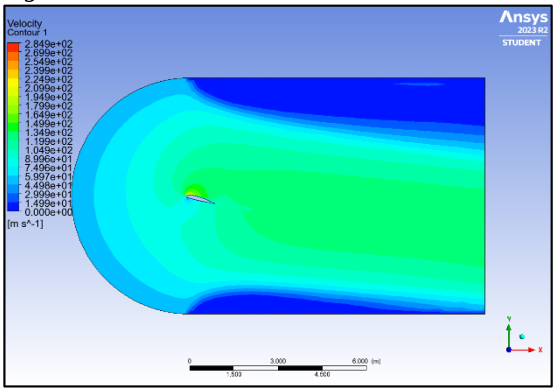


Figure 14 - AoA = 15

2. NACA 64A212

i. Pressure Distribution

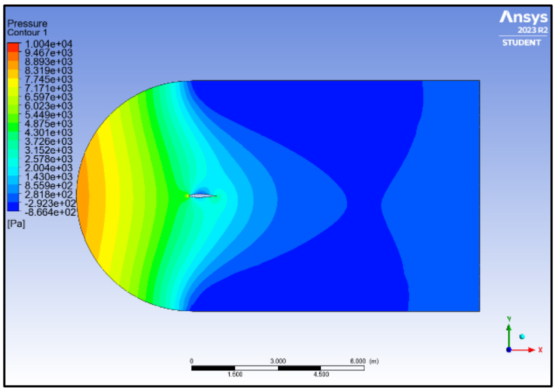


Figure 15 - AoA = 0

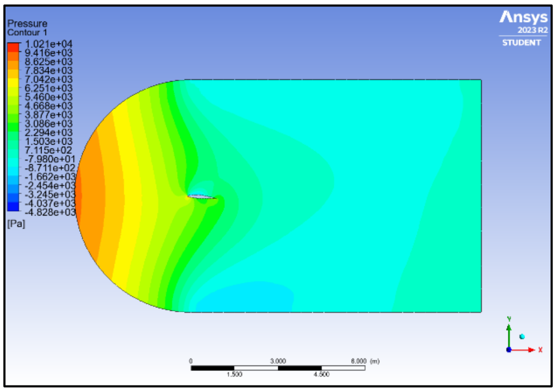


Figure 16 - AoA = 5

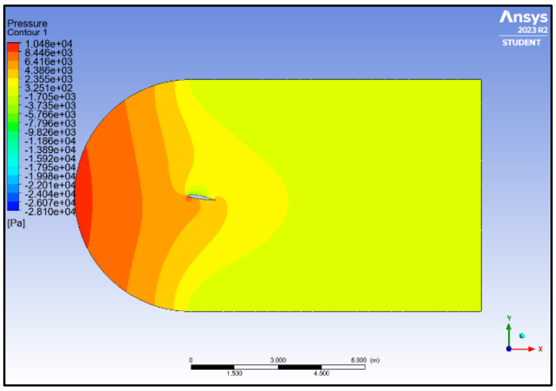


Figure 17 - AoA = 10

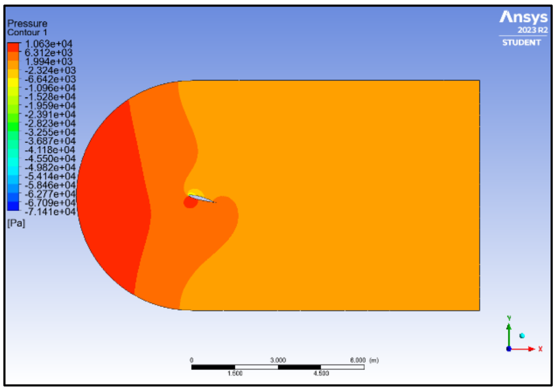


Figure 18 - AoA = 15

ii. Velocity Distribution

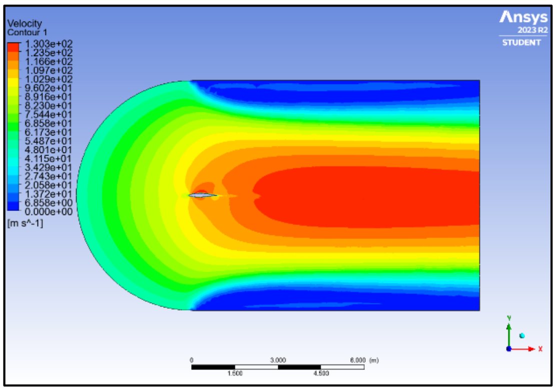


Figure 19 - AoA = 0

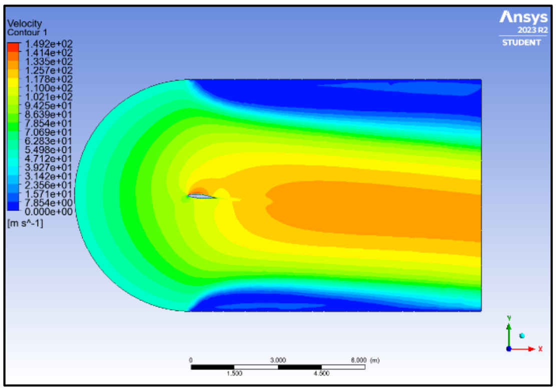


Figure 20 - AoA = 5

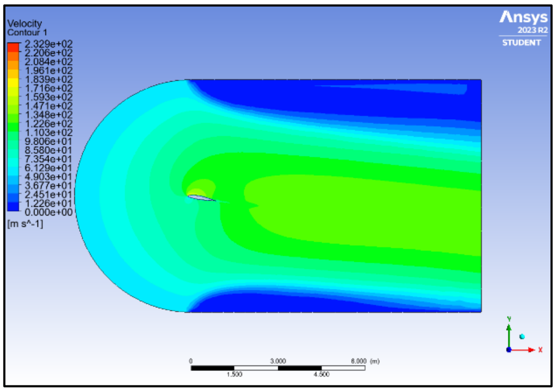


Figure 21 - AoA = 10

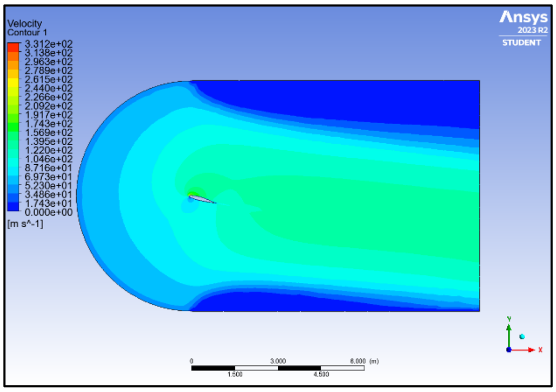


Figure 22 - AoA = 15

3. NACA 0012

i. Pressure Distribution

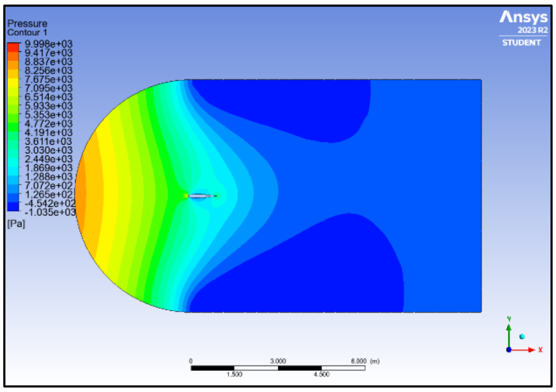


Figure 23 - AoA = 0

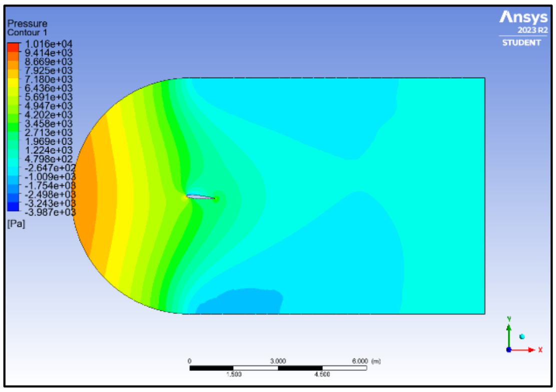


Figure 24 - AoA = 5

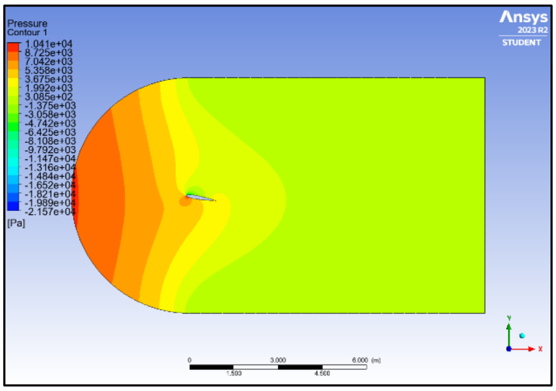


Figure 25 - AoA = 10

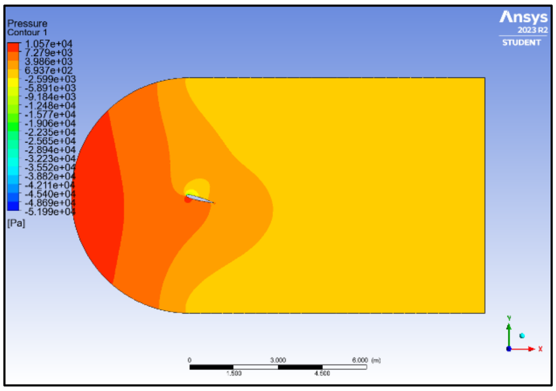


Figure 26 - AoA = 15

ii. Velocity Distribution

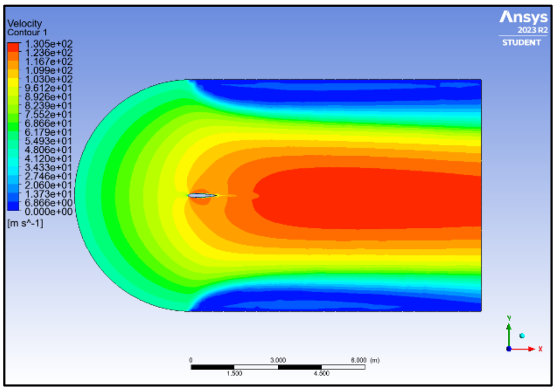


Figure 27 - AoA = 0

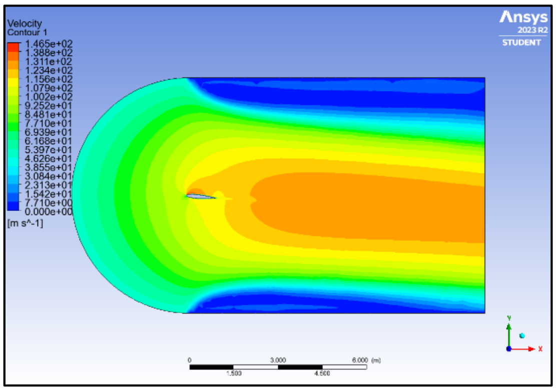


Figure 28 - AoA = 5

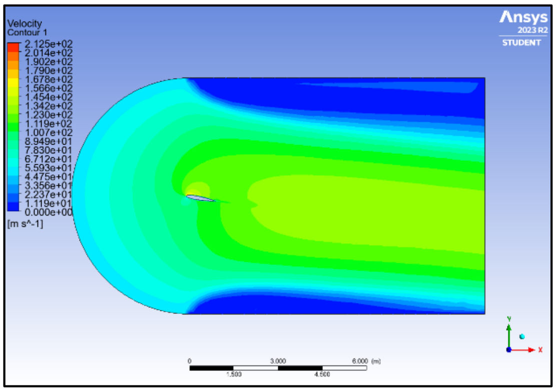


Figure 29 - AoA = 10

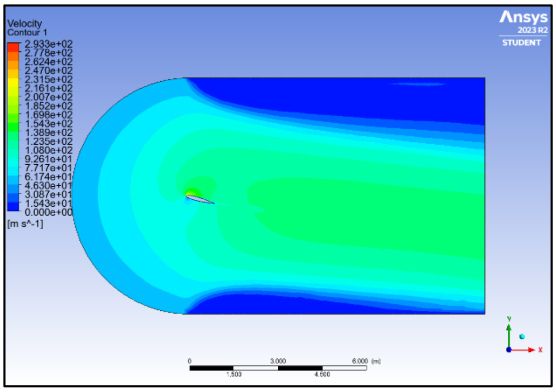


Figure 30 - AoA = 15

4. NACA 23012

i. Pressure Distribution

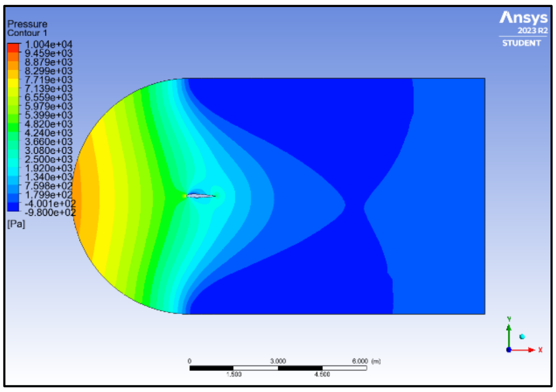


Figure 31 - AoA = 0

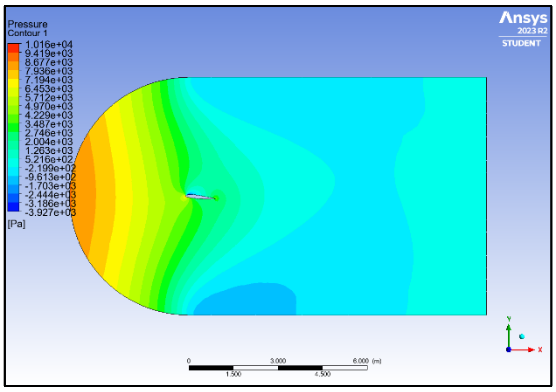


Figure 32 - AoA = 5

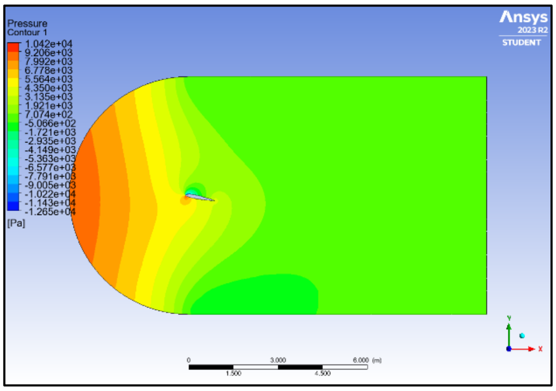


Figure 33 - AoA = 10

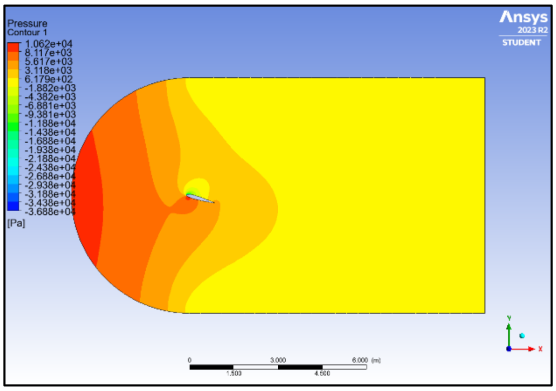


Figure 34 - AoA = 15

ii. Velocity Distribution

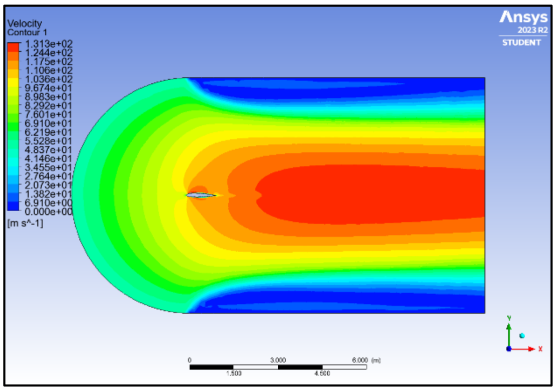


Figure 35 - AoA = 0

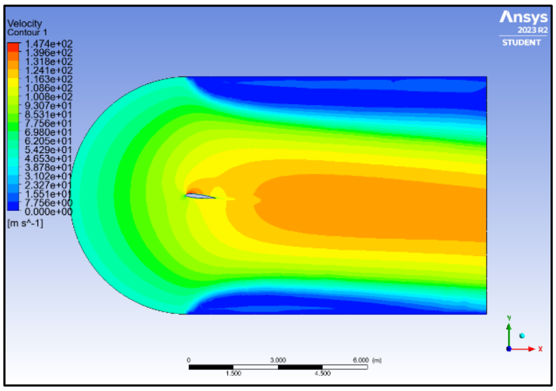


Figure 36 - AoA = 5

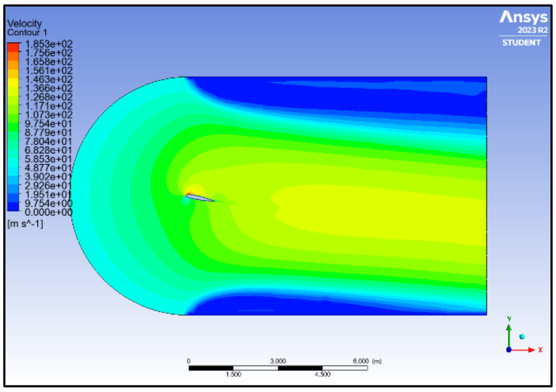


Figure 37 - AoA = 10

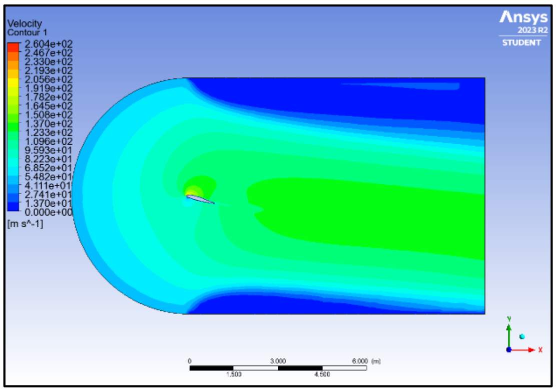
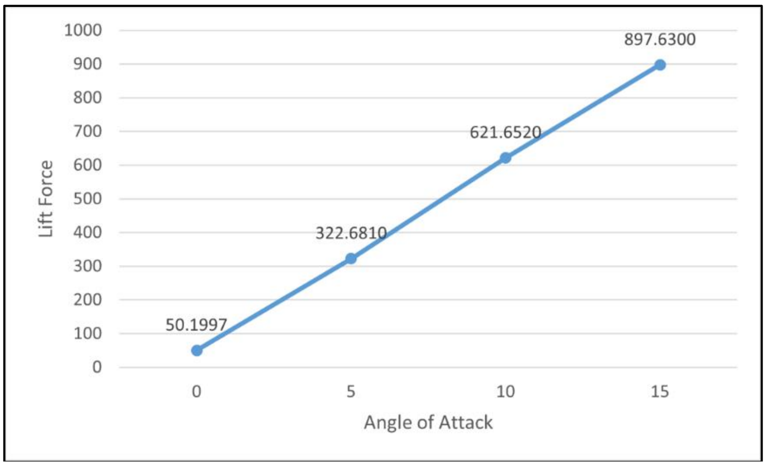


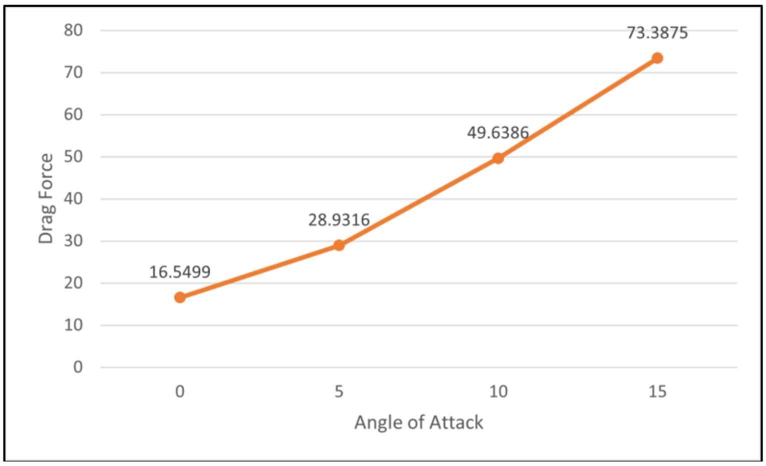
Figure 38 - AoA = 15

XI. AIRFOIL GRAPHS:

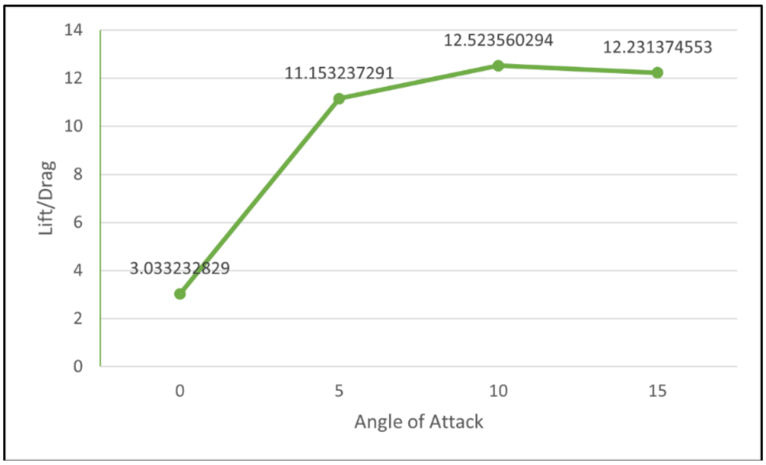
1. NACA 2412



Graph 1 - Lift Force vs Angle of Attack

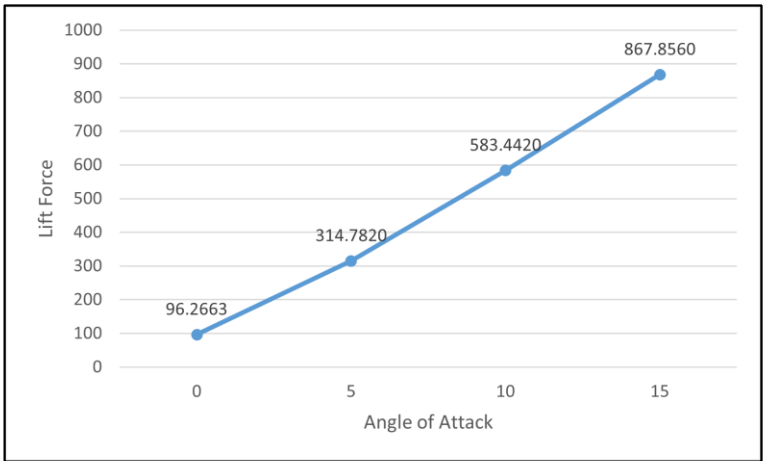


Graph 2 - Drag Force vs Angle of Attack

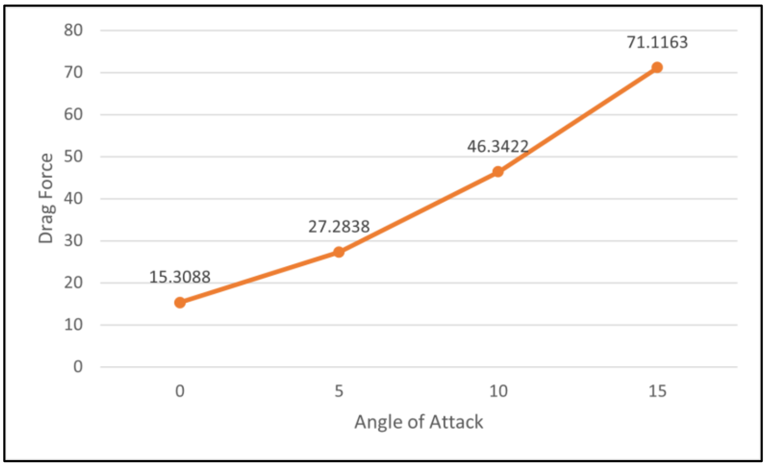


Graph 3 - Lift Force/ Drag Force vs Angle of Attack

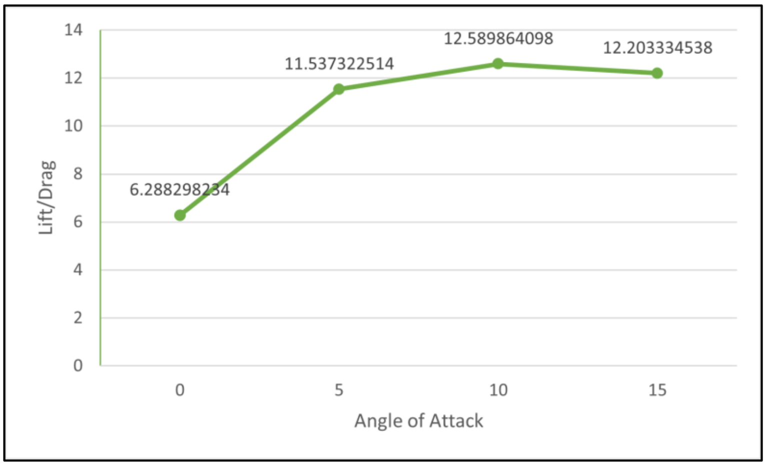
2. NACA 64A212



Graph 4 - Lift Force vs Angle of Attack

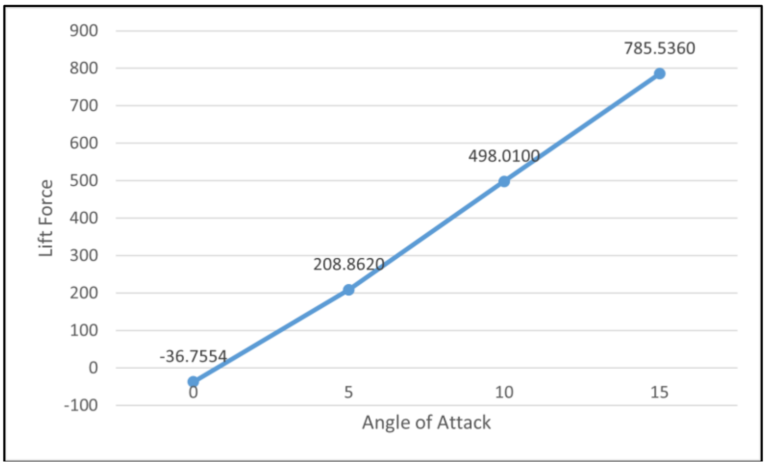


Graph 5 - Drag Force vs Angle of Attack

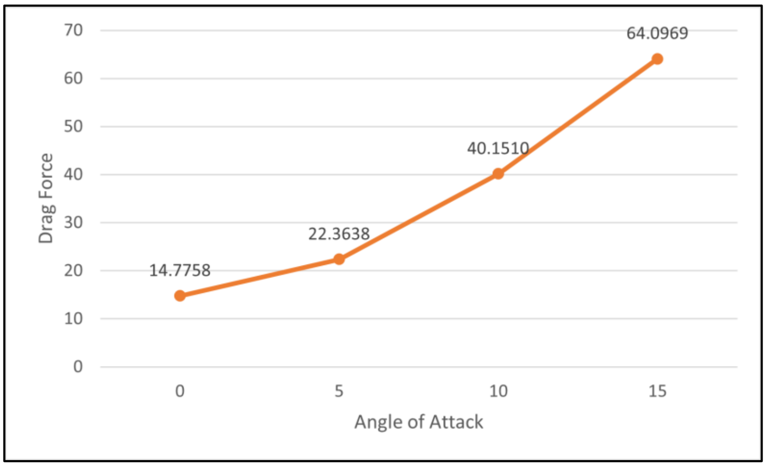


Graph 6 - Lift Force/ Drag Force vs Angle of Attack

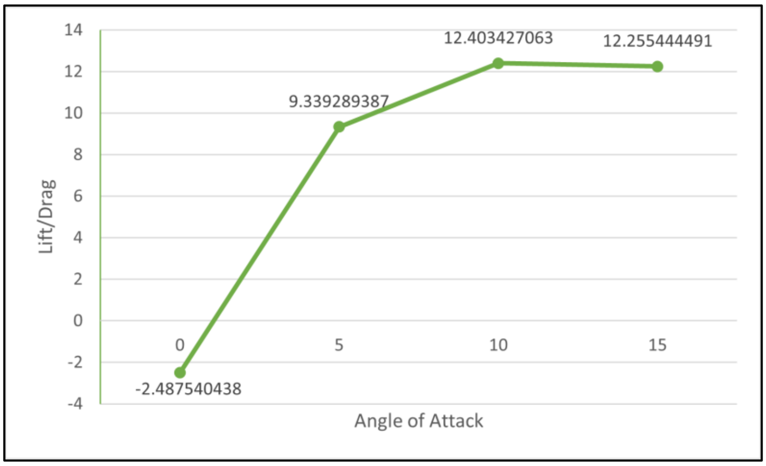
3. NACA 0012



Graph 7 - Lift Force vs Angle of Attack

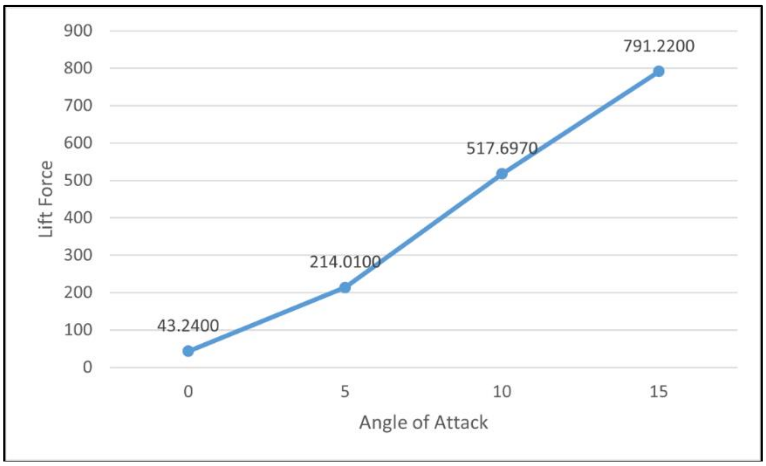


Graph 8 - Drag Force vs Angle of Attack

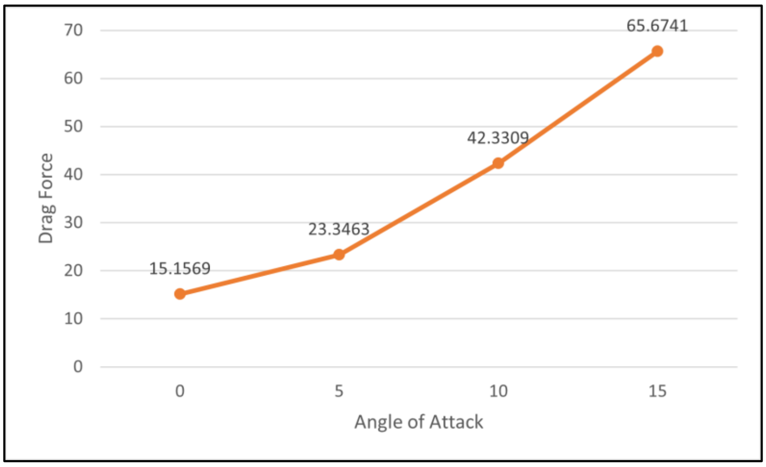


Graph 9 - Lift Force/ Drag Force vs Angle of Attack

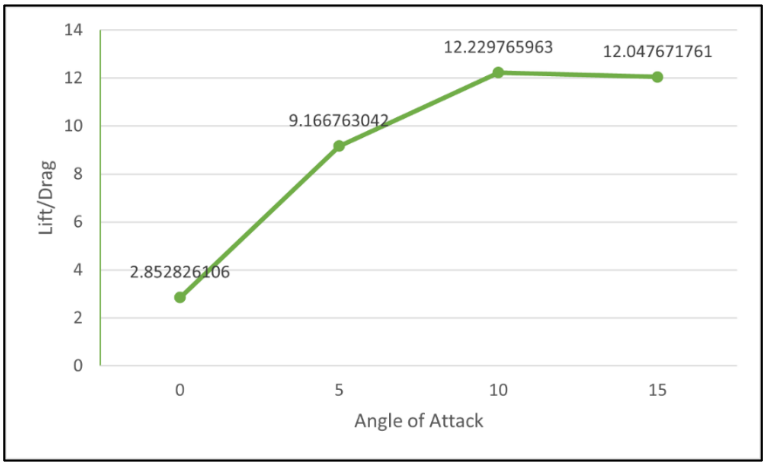
4. NACA 23012



Graph 10 - Lift Force vs Angle of Attack

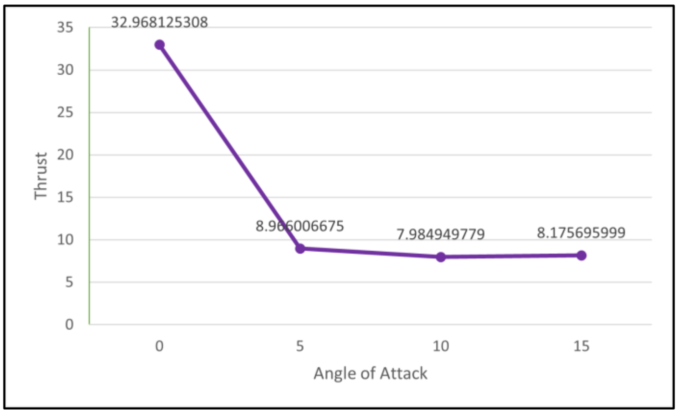


Graph 11 - Drag Force vs Angle of Attack

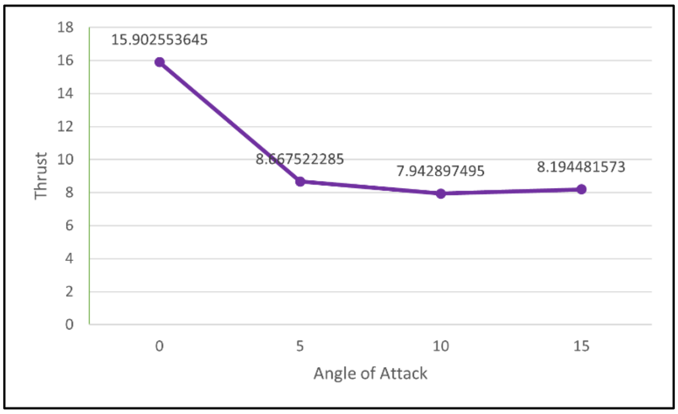


Graph 12 - Lift Force/ Drag Force vs Angle of Attack

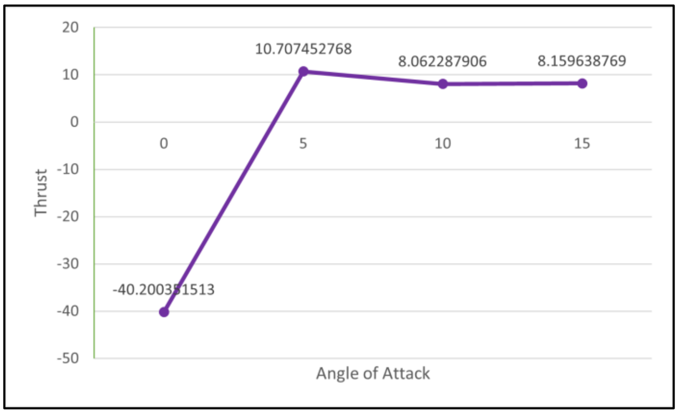
5. THRUST VS AOA FOR ALL AIRFOILS



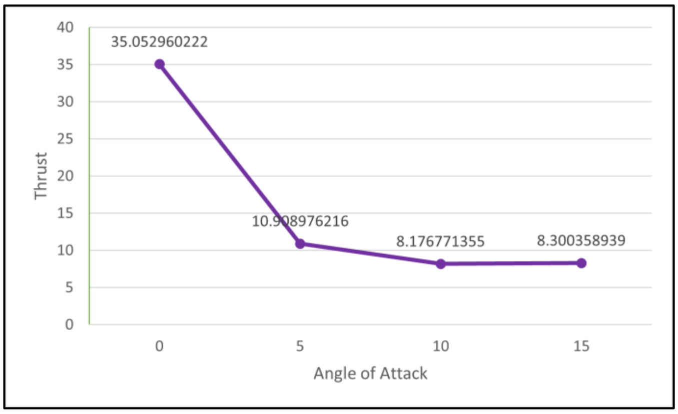
Graph 13 - NACA 2412



Graph 14 - NACA 64A212

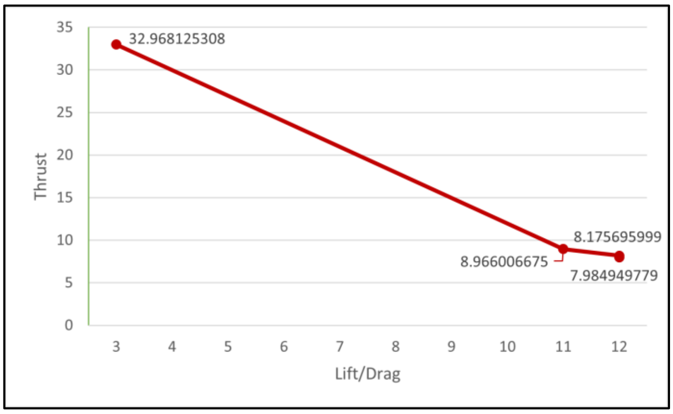


Graph 15 - NACA 0012

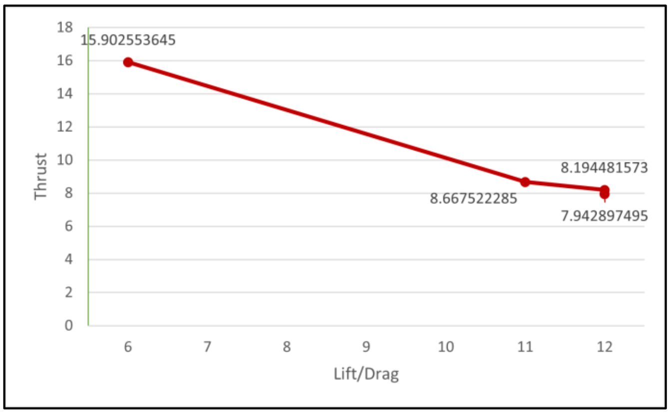


Graph 16 - NACA 23012

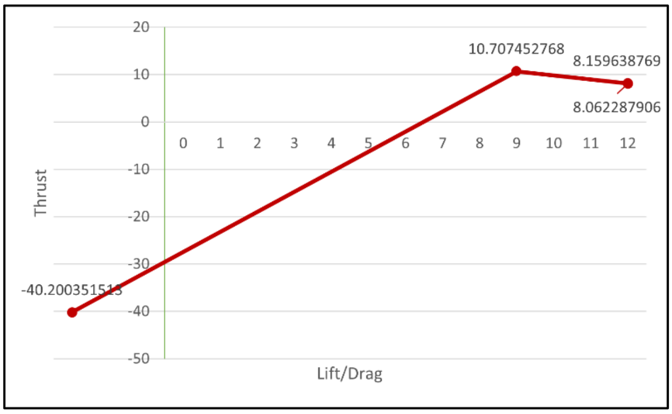
6. THRUST VS LIFT/DRAG FOR ALL AIRFOILS



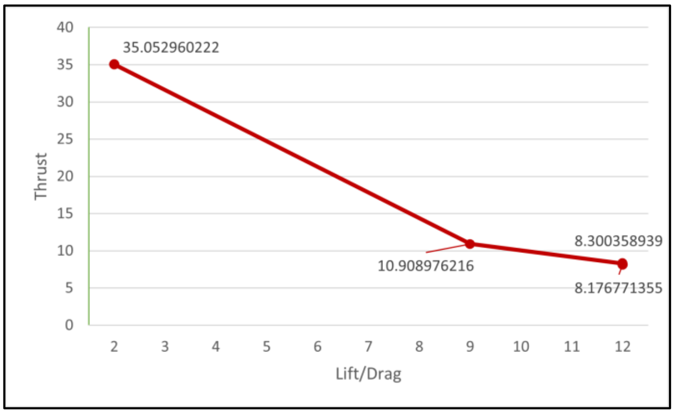
Graph 17 - NACA 2412



Graph 18 - NACA 64A212

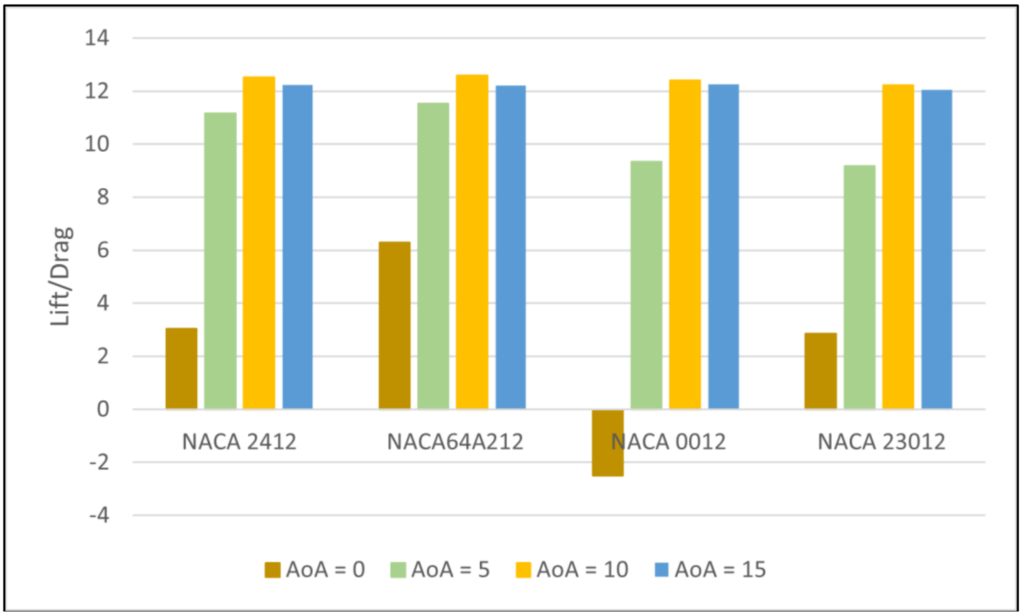


Graph 19 - NACA 0012



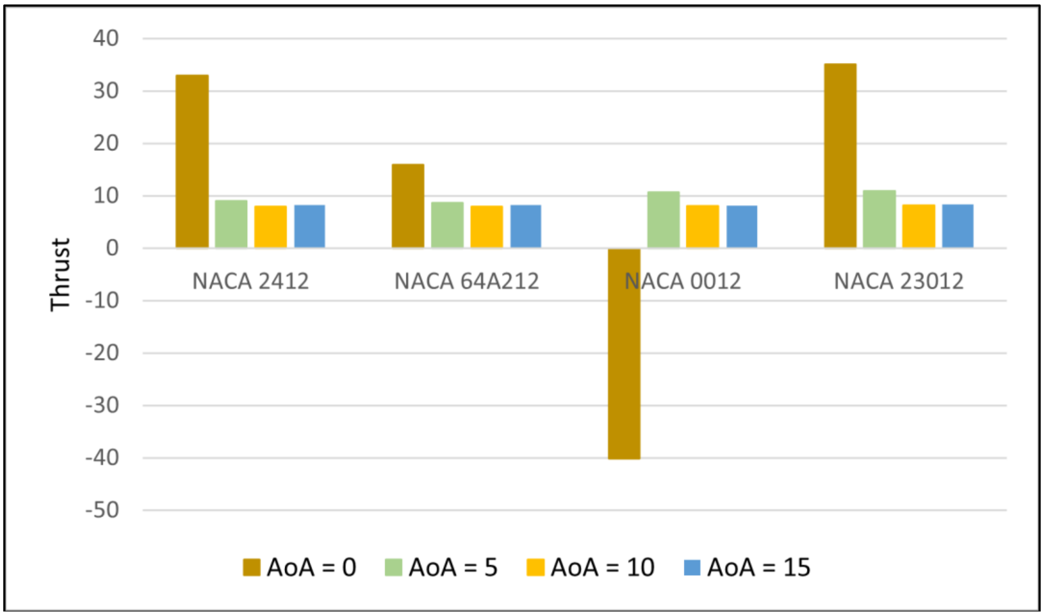
Graph 20 - NACA 23012

7. LIFT/DRAG VS AOA



Graph 21 - Lift Force/ Drag Force vs Angle of Attack for all Airfoils

8. THRUST VS AOA



Graph 22 - Thrust vs Angle of Attack for all Airfoils

XII. DISCUSSION AND CONCLUSION:

As illustrated in Graph 12, the NACA 23012 airfoil boasts a superior lift-to-drag ratio across various angles of attack. This translates to a lower thrust requirement compared to other NACA airfoils. We know from the thrust-to-weight ratio formula that a higher lift/drag value translates to less thrust needed, ultimately enhancing fuel efficiency and overall aerodynamic performance. This translates into a clear advantage for aircraft using the NACA 23012 airfoil. They require less energy to maintain flight and maneuver, leading to improved operational efficiency. Consequently, aircraft equipped with this design can achieve greater range and endurance while consuming less fuel. These aerodynamic benefits are particularly crucial for applications where fuel economy and extended flight times are essential, such as long-range passenger flights or unmanned aerial vehicles (UAVs) with demanding mission durations. By prioritizing aerodynamic efficiency through strategic selection of airfoil profiles, engineers can significantly enhance the overall performance and mission capabilities of aircraft, paving the way for advancements in sustainable aviation technology.

Building on the success of the NACA 23012, the NACA 2412 airfoil offers another compelling option with impressive aerodynamic efficiency. Its moderate chamber thickness makes it a versatile choice for various aerospace applications. Both the NACA 23012 and NACA 2412 excel in wing designs where achieving a desired lift is paramount.

In contrast, airfoils like the NACA 0012 and NACA 64A212 have a significantly higher chamber thickness. While this feature bolsters structural stability, the results clearly show a trade-off in aerodynamic efficiency. These airfoils find their niche in specific engineering applications that prioritize structural strength over peak aerodynamic performance. They are ideal when a lower lift value and enhanced structural integrity are essential design considerations.

The analysis of the NACA 23012 airfoil reveals its strength in generating lift at lower angles of attack. This translates to two key benefits. Firstly, it requires less thrust compared to other airfoils at these angles. Secondly, it allows for achieving higher lift coefficients at lower angles of attack. Both factors contribute to the overall fuel efficiency of the airfoil. Since less thrust is needed to maintain lift, the aircraft using this design experiences significant fuel savings.

The NACA 23012 airfoil's strength at lower angles of attack extends beyond just fuel efficiency. Its ability to generate higher lift at these angles translates to several performance advantages. These include shorter take-off distances, improved climb rates, and enhanced maneuverability. All of this can be achieved while still minimizing fuel consumption. This combination of efficiency and performance makes the NACA 23012 airfoil a very attractive choice for aircraft design, particularly for applications where both fuel savings and strong aerodynamic performance are crucial.

The NACA 0012 airfoil, being symmetrical, shouldn't exhibit negative lift coefficients as shown in Table 4, especially at zero angle of attack. Firstly, there's a remote possibility of encountering negative lift at very low Reynolds numbers (around 10,000-20,000) due to specific flow phenomena. However, this is uncommon and not representative of typical airflow behaviour. However, this is not standard airflow behaviour. Secondly, we can consider any external factors influencing the airflow. High turbulence can potentially cause unexpected lift results at low angles of attack.

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11. https://m-selig.ae.illinois.edu/ads/aircraft.html (University of Illinois airfoil database)
12. http://airfoiltools.com/airfoil/details?airfoil=naca4412-il (Airfoil data for NACA4412)
13. http://airfoiltools.com/airfoil/details?airfoil=naca23012-il (Airfoil data for NACA23012)

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