

Numerical Analysis of Influence of Inward Dimples on Aerodynamic Characteristics of Symmetrical Airfoil Using CFD

Parthasarathy G*, Sibin Raj T, Vijeth CM

Department of Aeronautical Engineering, Acharya Institute of Technology, Soladevanahalli, Bangalore, India

ABSTRACT

This project represents a comprehensive exploration into the design and numerical analysis of an aircraft wing using an inward dimple. Dimples are a small indentations on the surface that looks like a very small craters. Dimples on the airfoil surface delay the separation of the boundary layer and delays the separation of flow stage. Dimples also produce turbulence that results in the delay of separation of boundary layer and decreases the formation of wake. Due to dimples airfoil will have irregular surface, so that the detachment of the flow will be delayed that makes flow stick to the surface. The airfoil will comparatively have less pressure drag than the plain airfoil.

Keywords: Dimples; Pressure drag; Manoeuvrability; Aerodynamic; Aerofoil

Abbreviations: CFD: Computational Fluid Dynamics

INTRODUCTION

The aviation industry today is the safest and most efficient it has been since the first aircraft was invented. Continuous attempts are being made to increase freedom in air, be it speed, size or manoeuvrability. An aerofoil is an aerodynamic body so dimples do not affect to its drag much at zero angle of attack, but as soon as aerofoil attains some angle of attack, wake formation starts due to boundary layer separation. In the present study we analyse the effect of circular inward dimple on the flow characteristics of NACA 0021 symmetric aerofoil by varying the dimple's position on the chord length. The computational study is done with the help of ANSYS and results were obtained from the same. The results are analysed and conclusions are made from it [1].

In the relentless pursuit of aerodynamic efficiency, engineers and researchers have continually sought innovative methods to improve aircraft performance. One such avenue of exploration has led to the integration of dimpled surfaces into aircraft design. Derived from nature's own blueprint and inspired by the dimpled texture of a golf ball, this approach holds promise in revolutionizing aerodynamics.

Dimples, which are small, rounded indentations on a surface, have long been recognized for their ability to manipulate airflow. The concept gained prominence in sports equipment, notably in

golf balls, where dimples were found to reduce drag and enhance lift, resulting in greater distance and accuracy in flight. Translating this principle to aircraft surfaces presents a compelling proposition for optimizing aerodynamic performance [2].

At its core, the integration of dimples into aircraft design seeks to achieve several key objectives:

In conclusion, the integration of dimpled surfaces into aircraft design represents a captivating avenue for advancing aerodynamic efficiency and performance. By drawing inspiration from nature and leveraging cutting-edge engineering principles, researchers and engineers continue to push the boundaries of aviation technology, with the ultimate aim of enhancing safety, sustainability, and operational excellence in air transportation.

In the realm of aerospace engineering, the pursuit of aerodynamic efficiency is ceaseless. As aircraft design evolves, novel approaches are continually explored to enhance performance, fuel efficiency, and environmental sustainability. One such avenue of exploration involves the integration of inward dimples into aircraft surfaces, presenting a paradigm shift in aerodynamic optimization [3].

Derived from the natural world and inspired by the remarkable properties of inward dimples, this innovative approach holds

Correspondence to: Parthasarathy G, Department of Aeronautical Engineering, Acharya Institute of Technology, Soladevanahalli, Bangalore, India; E-mail: parthasarathy.aero@gmail.com

Received: 18-Dec-2024, Manuscript No. JAAE-24-35941; **Editor assigned:** 21-Dec-2024, PreQC No. JAAE-24-35941 (PQ); **Reviewed:** 04-Jan-2025, QC No. JAAE-24-35941; **Revised:** 10-Jul-2025, Manuscript No. JAAE-24-35941 (R); **Published:** 17-Jul-2025, DOI: 10.35248/2168-9792.25.14.378

Citation: Parthasarathy G, Raj ST, Vijeth CM (2025) Numerical Analysis of Influence of Inward Dimples on Aerodynamic Characteristics of Symmetrical Airfoil Using CFD. J Aeronaut Aerospace Eng. 14:378.

Copyright: © 2025 Parthasarathy G, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

tremendous potential to revolutionize aircraft performance. By strategically incorporating these features into critical aerodynamic surfaces, engineers seek to achieve unparalleled levels of efficiency and maneuverability while simultaneously reducing environmental impact.

Inward dimples, characterized by concave indentations on a surface, offer several distinct advantages in the context of aircraft performance:

By harnessing the principles of inward dimples, aerospace engineers aim to unlock new frontiers in aircraft performance and efficiency. Through interdisciplinary collaboration and rigorous experimentation, the aviation industry stands poised to realize the transformative potential of this innovative technology [4].

In conclusion, the integration of inward dimples into aircraft design represents a compelling leap forward in the quest for aerodynamic excellence. By capitalizing on nature-inspired solutions and cutting-edge engineering ingenuity, aircraft manufacturers and operators can elevate performance standards while simultaneously advancing the sustainability and environmental stewardship of air transportation. As the aviation landscape continues to evolve, inward dimples offer a promising pathway towards a greener, more efficient future in flight.

The integration of inward dimples disrupts airflow patterns in a manner that reduces drag, a formidable adversary to efficient flight. By controlling boundary layer turbulence and minimizing separation, inward dimples promote smoother airflow over surfaces, resulting in reduced drag and enhanced fuel efficiency [5].

The controlled airflow afforded by inward dimples serves to delay the onset of stall, a critical consideration in aircraft safety and performance. By maintaining laminar flow and reducing the likelihood of separation, these features enhance aerodynamic stability and control, particularly during low-speed flight regimes.

Turbulent airflow and aerodynamic noise pose significant challenges in aviation, impacting passenger comfort and environmental concerns. Inward dimples offer the potential to mitigate such noise by minimizing turbulent flow interactions and optimizing aerodynamic performance, thereby fostering a quieter and more pleasant flight experience. Inward dimples possess the capability to optimize lift generation by effectively managing airflow attachment and boundary layer dynamics. This phenomenon translates into improved lift-to-drag ratios, facilitating more efficient flight operations across a range of speeds and flight conditions [6].

This study aims to investigate the aerodynamic performance of inward dimples integrated into an aircraft wing, with a focus on drag reduction, lift enhancement, stall mitigation, and structural considerations. Through Computational Fluid Dynamics (CFD) simulations and structural analysis, the impact of inward dimples on aerodynamic efficiency and structural integrity will be evaluated. The specifications of the aircraft wing, including dimensions, airfoil profile, and operating conditions, will be provided to facilitate a thorough analysis. The findings of this

study will contribute to the understanding of the feasibility and effectiveness of using inward dimples for optimizing aircraft aerodynamics.

MATERIALS AND METHODS

E. Livya et al., did the modification in terms of dimples creates turbulence in order to delay flow separation, which increases the stall angle at which the aircraft is no longer controllable when air is not flowing over the wing properly [7].

T Gopikrishnan Kailas and Professor Reji Mathew performed for higher lift characteristics favorable places for dimples is trailing edge, while for better drag characteristics favorable places for dimples is leading edge. Karthik AT et al., observed that Percentage of pressure reduced after placing dimples is 58.42% percentage of velocity increased after placing dimples is 4.16%. Turbulence decreased from 88% to 83%. The turbulence should be decreased because increase in turbulence intensity leads to increase in pressure drag.

Zahra Mehtar and Afaq Altaf performed that spherical dimples have the best design performance of all other design modifications. There is a significant improvement in the boundary layer separation from the clean airfoil. Therefore, spherical dimples are the best design modification to delay flow separation and improve performance. Spherical dimples create tiny vortices in their concavities, which cause the boundary layer to become turbulent and remain attached for longer.

Arvind Mukundan performed that turbulence decreased from 88% to 83%. The turbulence should be decreased because increase in turbulence intensity leads to increase in pressure drag.

Md. Amzad Hossain et al., has observed that the flow separation on the surface of the airfoil can be delayed by the modification with dimples on the surface. The attached flow on the dimpled surface is appeared at higher attack angle than the smooth surface. The lift of dimpled surface airfoil will be greater than the smooth surface. Airfoil with inward dimples has, overall, the best performance, giving about approximately 16.43% increase in lift and approximately 46.66% of reduction in drag as compared to without dimpled airfoil and it is giving the best lift/drag ratio. For inward dimpled airfoil there is approximately 21.6% increase in lift to drag ratio [8].

Zheng Pei Soh et al., has performed that the current study confirms that the most efficient or best dimple's shape is an ellipse. Introducing an ellipse dimple on the lower surface of the airfoil does improve the aerodynamic efficiency for all the AOA that have been studied in this paper. By comparing to the AOA that takes into consideration in this study, the effectiveness of the dimple is higher at low angle of attack for all of the shapes of dimple.

Amit Kumar Saraf et al., coefficient of lift and drag were analysed and compared at positive angle of attack. It shows that coefficient of lift has been increased by 7% for airfoil having dimple at 75% of chord length, compared to smooth airfoil. In the same manner it was noticed for coefficient of drag. Coefficient of drag has been reduced by 3% for the same airfoil.

The location of the dimple on the airfoil plays an important role. In this work we noticed that dimple at 75% of the chord length is the best location for the dimples.

Mohammad Mashud et al., has performed that the pressure coefficient, the coefficient of lift, the coefficient of drag, the lift to drag ratio is investigated in the experiment and compare with modified surface. Due to dimples on upper surface of airfoil it has been seen that flow separation is delayed. The lift has been increased about 13% and approximately 21.6% drag has been reduced and model with dimples gives best lift to drag ratio than regular surface model. The experiment is performed at different three speeds. And it is seen that with increasing Reynolds number the coefficient of lift is slightly increased on the other hand coefficient of drag is decreased [9].

P. Booma Devi and Dilip A Shah has performed that the non-linear characteristics of symmetrical airfoil NACA 0012 are characterised by the inward cavities which placed root to tip. At very low Reynolds number the laminar flow separation occurred as the angle of attack increased periodically. The overall stalling angle exhibits an increase of 180 from 150. The numerical simulation also indicates the dimple airfoil configuration gives better aerodynamic efficiency compared to plain aerofoil. The numerical simulation also indicates the dimple airfoil configuration gives better aerodynamic efficiency compared to plain aerofoil. The intensity of the cavity increases the lift coefficient and decreases the drag coefficient.

Modeling and analysing

Dimples: Dimple is a slight depression in the surface of an object. Dimples can make the air flow attached to the surface of the wing for a slight long period by making the flow separation on the surface occurring late. This continuous flow on the wing will be smooth without any whirls and will flow out of the surface without forming much wakes. This reduces the pressure drag created on the surface of the wing. In this work dimples are arranged from the leading edge towards the trailing edge spread across the surface of the wing, leaving space for lift generating components and other necessary components like flaps and ailerons. Dimples are also made with varying depth with equal radius along the wing surface to make sure that none of the dimple clashes on either side. The dimple is also not too shallow because shallow dimples can make way for quick flow separation which increases pressure drag.

Figure 1 shows the side view of dimple that is made on the aircraft wing surface. The dimensions taken are to make sure

that dimple on either side doesn't collide and also it is safe for the placement of flaps and ailerons to create lift. Dimples are placed on top and the bottom side of the wing to make the air flow through the wing surface evenly to reduce the pressure drag on the wing surface.

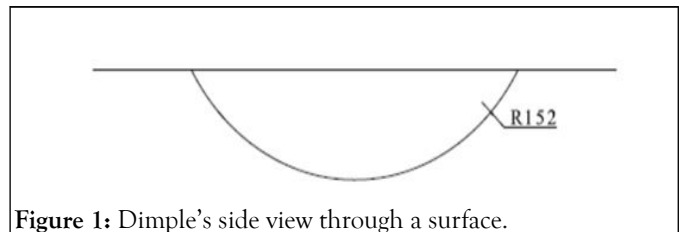


Figure 1: Dimple's side view through a surface.

Figure 2 shows the dimple on a surface. The dimple is a smooth arc type dimple that can give a good air flow over the surface. Arc shape dimple is chosen because according to Katsumi Aoki, Koji Muto, Hiroo Okanaga and Yasuki Nakayama the smooth arc type dimple gives best results of smooth airflow compared to other shape dimples.

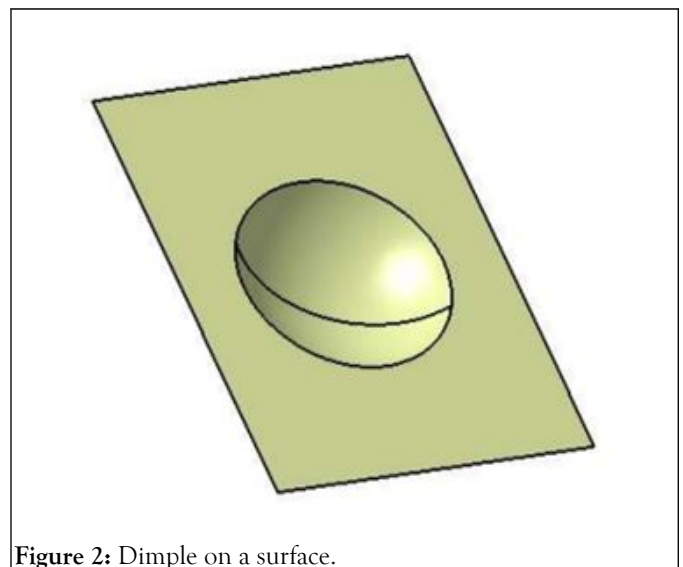


Figure 2: Dimple on a surface.

Analysing using computational fluid dynamics: Ansys Fluent software is the most-powerful computational fluid dynamics tool available, empowering to go further and faster as optimizing the wing's performance. Fluent includes well validated physical modelling capabilities to deliver fast, accurate results across the widest range of CFD and multi physics applications. So, we use Ansys Fluent as the software to do CFD analysis. The velocity of air used for analysis is 30 ms^{-1} (Table 1).

Table 1: Specifications and boundary conditions.

S. no	Parameters	Values
1	Series code	NACA 0021
2	Velocity	30 m/s
3	Density	1.225 kg/m^3
2	Maximum thickness	21% at 30% of chord

3	Camber	0
4	Chord length	100 mm
5	Dimple location	30% of chord
		60% of chord

Scope of report of CFD simulations

The report aims to conduct a numerical analysis of an aircraft wing incorporating inward dimples, assessing their impact on aerodynamic performance and structural integrity. By employing computational methods, the study seeks to quantify changes in lift, drag, and stability, as well as stress distribution within the wing structure. Additionally, the report will explore the feasibility of implementing inward dimples for enhancing aerodynamic efficiency while ensuring structural robustness. Results will provide insights into the potential benefits and challenges associated with this innovative design approach, offering valuable information for aircraft engineers and designers.

Numerical analysis

The methodology for the numerical analysis of an airfoil with inward dimples involves several steps, including defining the geometry, setting up the numerical simulations, and analyzing the results.

Here's a detailed methodology for conducting such an analysis.

Airfoil geometry definition: Choose an appropriate airfoil profile for analysis. Common choices include NACA airfoils or custom-designed profiles. Introduce inward dimples to the airfoil geometry. Dimple size, shape and distribution should be specified based on the intended objectives of the analysis.

Mesh generation: Create a computational mesh around the airfoil geometry. This mesh should have sufficient resolution to capture boundary layer effects, flow separation, and interactions with the dimples. Use techniques such as structured or unstructured meshing depending on the complexity of the geometry and the flow regime.

Numerical simulation setup: Select appropriate numerical solvers for simulating fluid flow around the airfoil. Common choices include Reynolds-Averaged Navier-Stokes (RANS) or Large Eddy Simulation (LES) methods.

Specify boundary conditions including free stream velocity, angle of attack, and turbulence model parameters. Set up the simulation to include the effects of the inward dimples on the airfoil surface. This may involve specifying additional boundary conditions or modifying the geometry representation.

Aerodynamic analysis: Run the numerical simulations to compute aerodynamic coefficients such as lift, drag, and moment coefficients. Monitor convergence of the solution and ensure that numerical errors are within acceptable limits.

Analyze flow patterns around the airfoil to identify any changes induced by the presence of inward dimples.

Structural analysis: If structural analysis is part of the study, couple the aerodynamic simulations with structural mechanics solvers. Compute stress distributions, deformation, and other structural properties of the airfoil under the applied aerodynamic loads. Investigate how the inward dimples affect the structural integrity and performance of the airfoil.

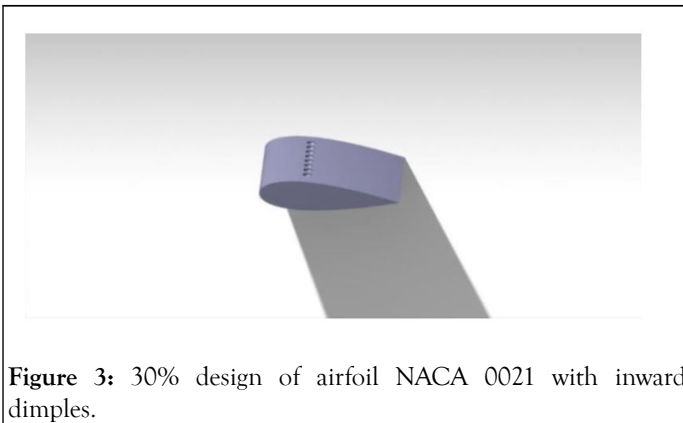
Post-processing and analysis: Visualize and interpret the numerical results using post-processing tools such as contour plots, streamlines, and velocity profiles. Compare the performance of the airfoil with and without inward dimples, focusing on changes in aerodynamic coefficients and structural responses. Extract quantitative data to support conclusions drawn from the analysis.

Sensitivity analysis and optimization: Conduct sensitivity analyses to understand the influence of dimple parameters (e.g., size, depth, location) on airfoil performance. Use optimization algorithms to improve the design of the inward dimples for specific objectives such as maximizing lift or reducing drag.

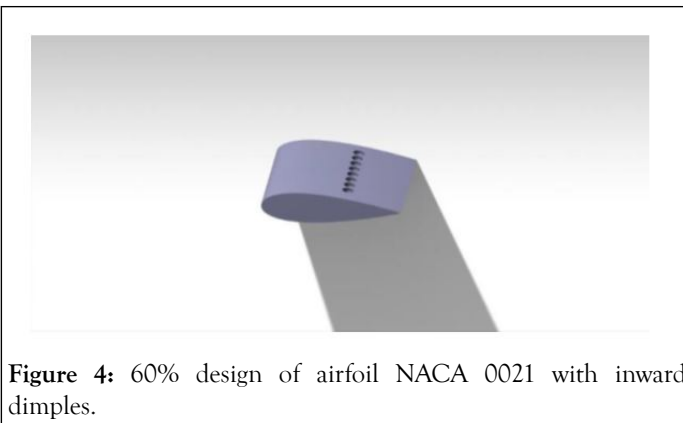
Validation: Validate the numerical results against experimental data or benchmark cases whenever possible to ensure the accuracy and reliability of the simulations.

Documentation and reporting: Document all aspects of the numerical analysis, including assumptions, methodologies, simulation settings, and results. Prepare a comprehensive report summarizing the findings of the analysis, including conclusions and recommendations for future studies. By following this methodology, researchers can effectively investigate the aerodynamic and structural behavior of airfoils with inward dimples using numerical simulations.

Designing an airfoil with inward dimples involves modifying the standard NACA 0021 airfoil geometry to incorporate dimples and then analyzing its aerodynamic performance using Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent. Here's a detailed guide on how to carry out a 30% design of an airfoil NACA 0021 with inward dimples in ANSYS (Figure 3).



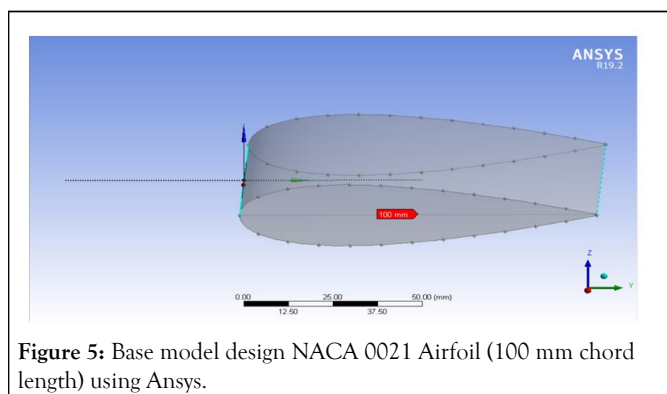
Designing an airfoil with inward dimples at 60% involves modifying the standard NACA 0021 airfoil geometry to incorporate dimples at this specific location and then analyzing its aerodynamic performance using computational fluid dynamics (CFD) simulations in ANSYS Fluent. Below is a detailed guide in ANSYS (Figure 4).



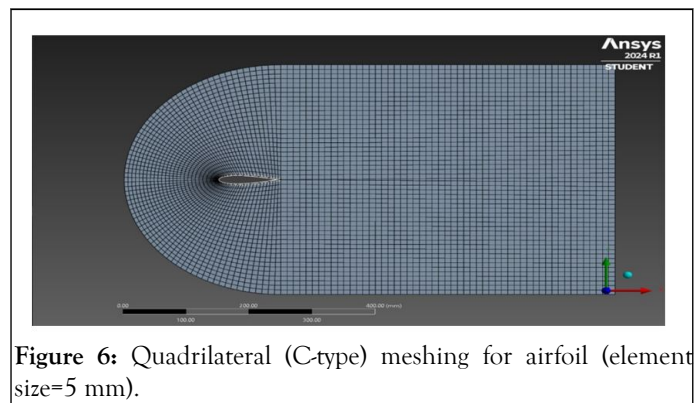
RESULTS AND DISCUSSION

Figures 5 and 6 shows the baseline wing model of the NACA 0021 Airfoil and meshing of this airfoil and the fluid domain done using ANSYS fluent.

Base model design of NACA 0021 airfoil

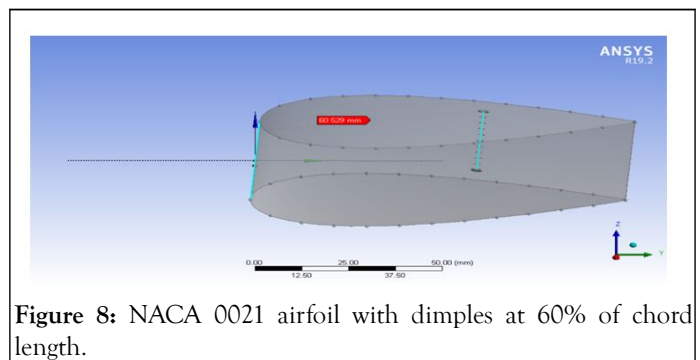
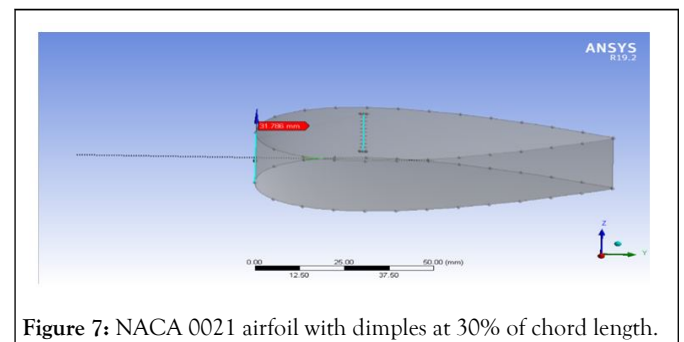


Meshing NACA 0021 Airfoil



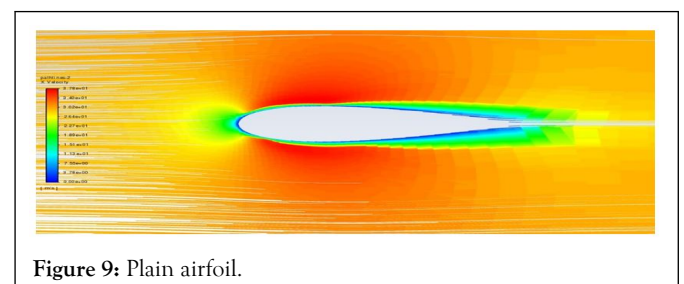
Meshing: It is the process of representing a geometric object as a set of finite elements for analysis. It is one of the most important and crucial processes in ANSYS.

Design of NACA 0021 airfoil with dimples at 30% and 60% of chord is shows in Figures 7 and 8.



Plots of velocity at 0 AOA

Circular dimple disrupts flow earlier, reducing flow separation and delaying turbulence onset, resulting in a more streamlined wake (Figures 9-11).



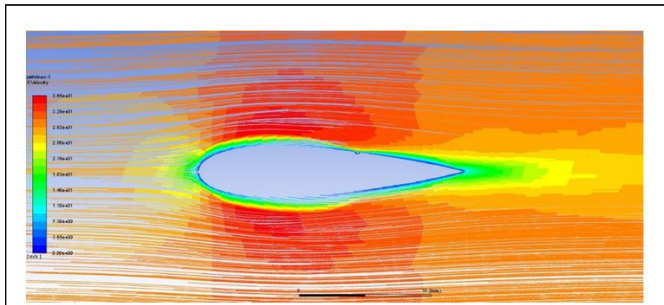


Figure 10: Airfoil with dimple at 30% of chord length.

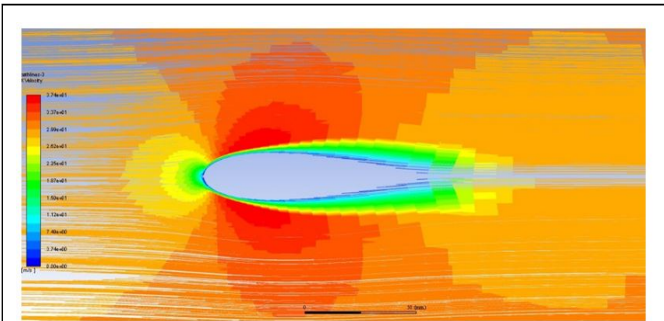


Figure 11: Airfoil with dimple at 60% of chord length.

Flow separation is observed closer to the leading edge due to lack of surface modifications, causing more turbulent wake regions.

Dimple positioned further back keeps flow attached longer over the chord, minimizing turbulence and wake size for maximum streamlining.

Plots of pressure at 0 AOA

Streamlined pressure path lines are smooth, with a relatively small pressure gradient across the surface (Figure 12).

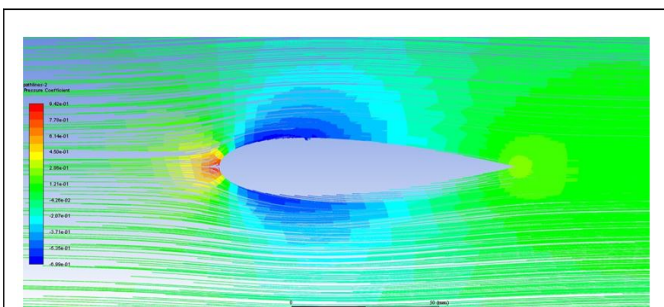


Figure 12: Plain airfoil.

Slight disturbances in pressure path lines in the front region, with localized high-pressure regions near the dimple. Improved boundary layer control over the forward portion (Figure 13).

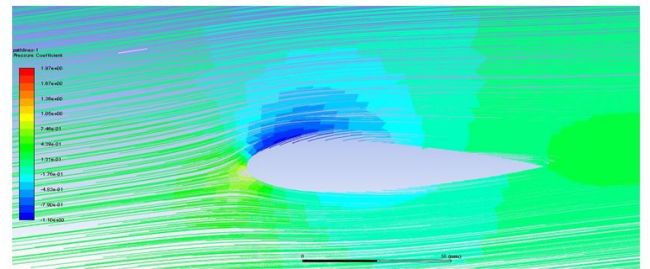


Figure 13: Airfoil with dimple at 30% of chord length.

More pronounced disturbances in pressure path lines downstream, with strong pressure retention and delayed separation (Figure 14).

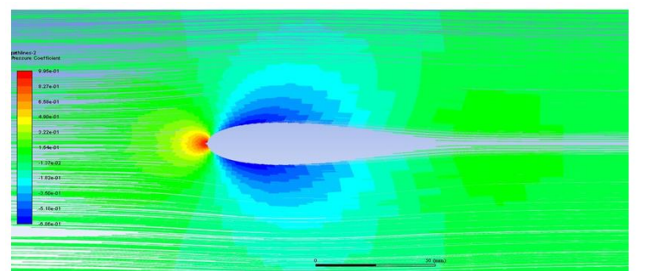


Figure 14: Airfoil with dimple at 60% of chord length.

Graphs

The aerodynamic performance of the baseline NACA 0021 model has been notably enhanced through the strategic implementation of dimples. As illustrated in the provided graph, the Coefficient of Lift (Cl) for the baseline model indicates relatively modest performance. However, upon conducting the same analysis with dimples strategically positioned at 30% distance from the leading edge, a discernible increase in the Cl value is evident. This enhancement underscores the effectiveness of dimples in optimizing aerodynamic lift, thereby improving the overall performance and efficiency of the NACA 0021 airfoil configuration. Such findings not only validate the utility of dimple incorporation in aerodynamic designs but also highlight the potential for further advancements in aircraft and automotive engineering (Figures 15 and 16).

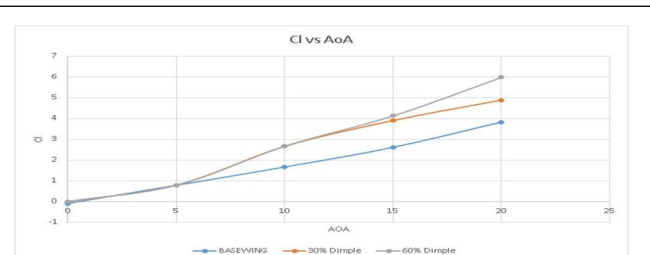


Figure 15: Cl vs. AoA.

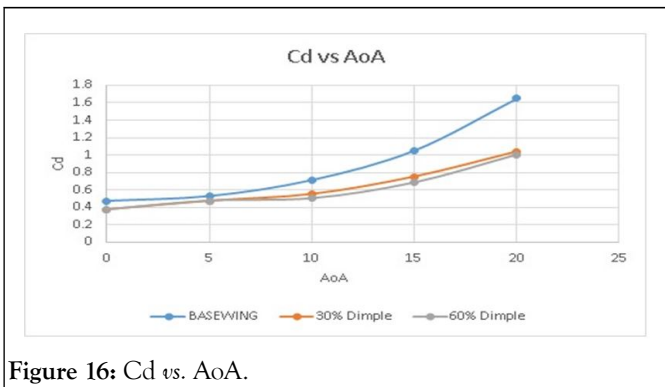


Figure 16: Cd vs. AoA.

Furthermore, when dimples are strategically inserted at 60% of the distance from the leading edge, the Coefficient of Lift (Cl) achieves its peak value among the three configurations. This significant observation underscores the profound impact of dimple placement on aerodynamic performance. By optimizing the positioning of dimples, engineers can harness enhanced lift generation capabilities, thus maximizing the efficiency and effectiveness of the NACA 0021 airfoil design. These findings not only highlight the versatility of dimple integration in aerodynamic enhancements but also emphasize the importance of meticulous analysis and experimentation in advancing aerospace and automotive engineering technologies. Such insights serve as valuable contributions to the ongoing pursuit of optimal aerodynamic solutions.

In contrast to the baseline model of the NACA 0021 airfoil, which exhibits comparatively high drag coefficient (Cd) values, the configurations with dimples strategically placed at 30% and 60% distances from the leading edge demonstrate notable reductions in Cd. This observation underscores the effectiveness of dimple integration in mitigating aerodynamic drag. By introducing dimples at these specific locations, engineers can optimize airflow and minimize drag forces, thereby enhancing the overall efficiency and performance of the airfoil design. Such findings highlight the potential of dimple technology to significantly improve aerodynamic characteristics and contribute to advancements in aerospace and automotive engineering. These insights underscore the importance of considering not only lift but also drag reduction strategies in the pursuit of optimal aerodynamic solutions for various applications. Mal aerodynamic solutions for diverse applications.

CONCLUSION

- From the obtained values, it is seen that the stall angle is increased using dimples. When the flow along the surface of

the airfoil enters a dimple, a small separation bubble is formed in the cavities. The consequence of the bubble formation is the acceleration of the flow between the dimples on the surface of the airfoil and boundary layer undergo a transition from laminar to turbulent. This transition leads to delay of separation of flow from the airfoil causing a substantial reduction of drag force.

- By disrupting the boundary layer separation and promoting smoother airflow over the air foil surface, the dimples effectively decrease turbulent flow and delay stall onset.
- The introduction of dimples at 60% has delayed the flow separation much better than at 30% which results in significant decrease in drag.
- A further analysis of the airfoil by changing the size of the dimple and even the shape and the location of the dimple could give a better and more accurate result of the effect of dimples.

REFERENCES

1. Valli PV, Anitha GA, Livya EL. Aerodynamic analysis of dimple effect on aircraft wing. *World Acad Sci Eng Technol Int J Aerosp Mech Eng*. 2015;9(2).
2. Kailas TKG, Mathew RM. Effect of circular shaped inward dimple on NACA 0021 airfoil. *Int J Res Dev Technol*. 2016;6(2).
3. Karthik KAK, Boniface VB, Sriram SS, Raj MG. Analysis of aerodynamic performance of aircraft wing attached with dimple using CFD. *Bonie Eng Technol Pvt Ltd*. 2016;18.
4. Mehtar ZM, Altaf AA. Influence of spherical and pyramidal dimples and bumps on airfoil performance in subsonic flow. *New York Institute of Technology School of Engineering and Computing Sciences*. 2021.
5. Mukundan AM. Analysis of an airfoil by changing the size, shape and location of dimple. *Int J Innov Sci Res Technol*. 2019;4(11).
6. Hossain MA, Uddin MN, Mustak R, Mashud M. Experimental study of aerodynamic characteristics of airfoils using different shaped dimples. *Int J Eng Sci*. 2015;4.
7. Saraf AK, Singh MP, Chouhan TS. Effect of dimple on aerodynamic behaviour of airfoil. *Int J Eng Technolss*. 2017.
8. Mashud M, Mondal D, Haque ME. Experimental investigation of an airfoil with multiple dimples on the upper surface. *Proc Int Conf Mech Eng Renew Energy*. 2017.
9. Devi PB, Shah DA. Numerical simulation of dimples in airfoil using MATLAB. *IOP Conf Ser Mater Sci Eng*. 2017.