

BIOMIMETIC DESIGN AND DEVELOPMENT OF DERMAL DENTICLE SHARK FOIL

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in
Aeronautical Engineering

By

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SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with grade "A++" by NAAC

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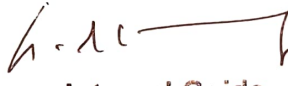
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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **ARJUN G (Reg. No.40260004)** and **MOSES THOMAS FELIX S (Reg. No. 40260703)** who carried out the project entitled "**BIOMIMETIC DESIGN AND DEVELOPMENT OF DERMAL DENTICLE SHARK FOIL**" under my supervision from June 2023 to April 2024.


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We, **ARJUN G (40260004)** and **MOSES THOMAS FELIX S (40260703)** hereby declare that the Project Report entitled "**BIOMIMETIC DESIGN AND DEVELOPMENT OF DERMAL DENTICLE SHARKFOIL**" done by us under the guidance of **Mr. G. MADHAN KUMAR, M.E., (Ph.D.,)** is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Aeronautical Engineering.



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ABSTRACT

The natural wonders of the sharkskin have attracted great attention in past decades. The slippery and textured shark skin has inspired biologists and engineers to design product with-like surfaces for better performance. The hydrodynamic behavior of a surface with shark-skin morphology has been reported to be improved. A shark skin like surface was composed of textured shark scaled with many micrometers sized grooves and ridges. The Denticle, a biomimetic approach for effective drag suppression in aero and hydrodynamic systems. The device aims to significantly enhance the aerodynamic efficiency. The primary focus of the device lies in pioneering a solution that optimizes the airflow by minimizing the drag and enhancing the performance across all the aero and hydrodynamic designs. The technology aims to streamline airflow dynamics, offering potential advancements in aerodynamic performance, ultimately reducing energy consumption and improving overall aerodynamic functionality.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

ABBREVIATION

α	Angle of Attack
CL	Coefficient of Lift
CD	Coefficient of Drag
CD _o	Coefficient of Skin Friction Drag
L/D	Lift-to-Drag Ratio
Re	Reynolds Number
NACA	National Advisory Committee for Aeronautics
RPM	Revolutions Per Minute

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CHAPTER – 1

INTRODUCTION

Biomimetics, also known as biomimicry or bioinspired design, is an innovative approach in engineering and design that draws inspiration from nature to solve complex human challenges. It involves studying and emulating biological systems, processes, structures and functions found in the natural world to create efficient, sustainable, and innovative solutions for various engineering and design problems. By understanding and adapting the natural strategies, engineers and designers can develop groundbreaking technologies, materials and systems that often outperform conventional human-made designs.

Thus, the application of biomimicry in the field of Aerospace industry mainly to improve the aerodynamic efficiency can be achieved by being inspired from the scales in the skin of the sharks which is also known as “Dermal Denticles”.

1.1 TYPES OF FLUID FLOW:

Fluid Flow refers to the movement or the motion of a fluid substance, such as a gas or a liquid. It is a fundamental concept in fluid dynamics, which is the study of how fluids behave when they are in motion or at rest. Fluid flow can occur in a wide range of contexts, from the flow of air around an airplane wing to the flow of water through pipes in a plumbing system.

In Aerodynamics, fluid flow can be categorized into several types based on various characteristics such as speed, viscosity, compressibility and behaviour and the categorization are as follows:

- Steady / Unsteady Flow
- Compressible / Incompressible Flows
- Laminar / Turbulent Flows
- Viscous / Inviscid Flows
- Rotational / Irrotational Flows

1.1.1 Steady / Unsteady Flow:

In Steady flow, the velocity, pressure, and other flow parameters at any given point in the fluid remain constant over time. This means that the flow pattern does not change with time, offering stability in analysis and design processes.

Unsteady flow is characterized by changes in flow parameters over time at certain points in the flow field. This could result from time-varying boundary conditions, transient disturbances or periodic fluctuations. Understanding unsteady flow is crucial for periodic dynamic behaviours in systems like oscillating airfoils or unsteady flow around structures.

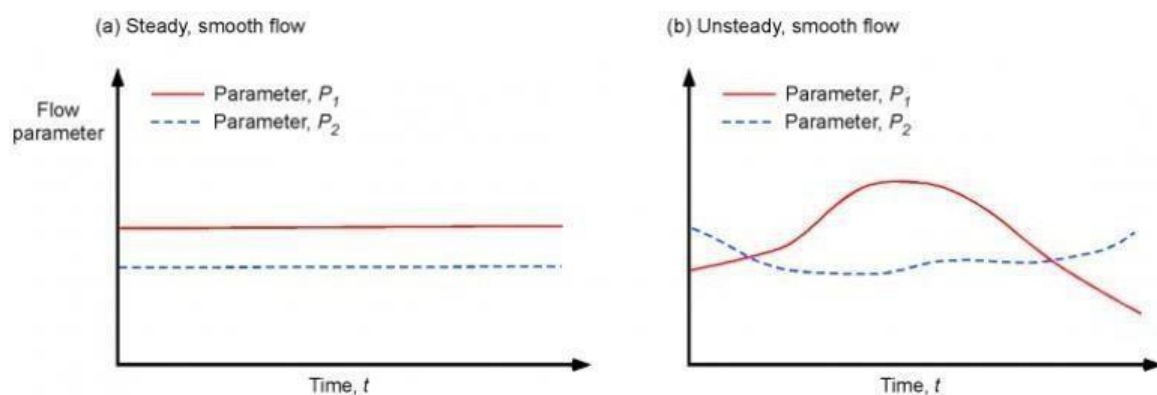


Fig:1.1 : Steady and Unsteady Flow

1.1.2 Compressible / Incompressible Flow:

Compressible Flow involves variations in fluid density due to changes in pressure, temperature and velocity. This type of flow is significant at high speeds or when dealing with gases like air under non-standard conditions. Compressibility effects become crucial in supersonic and hypersonic aerodynamics, where changes in density significantly affect flow behaviour.

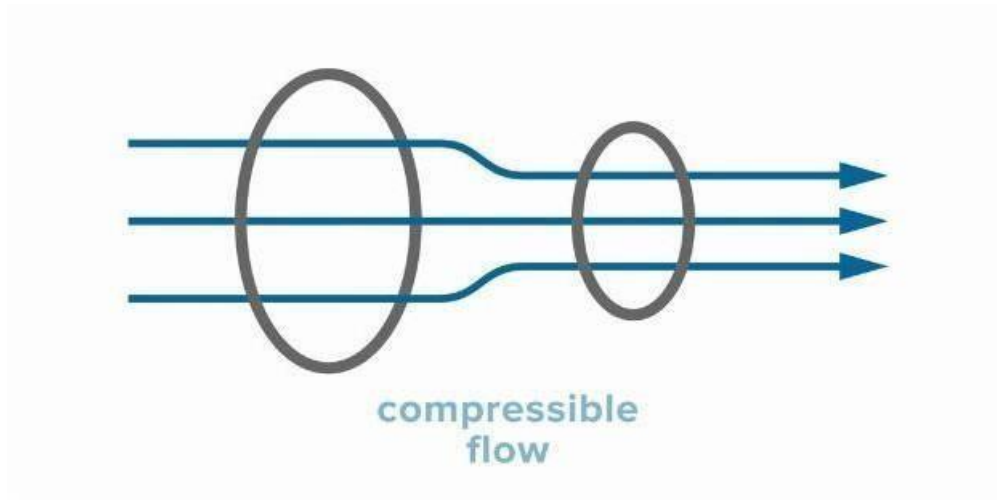


Fig:1.2 : Compressible Flow

In Incompressible flow, the density of the fluid remains constant throughout the flow field, meaning the fluid cannot be significantly compressed. This simplifies analysis, particularly at low speeds and in situation where density changes due to flow velocity are negligible, such as in many aerodynamic applications involving air at moderate speeds.

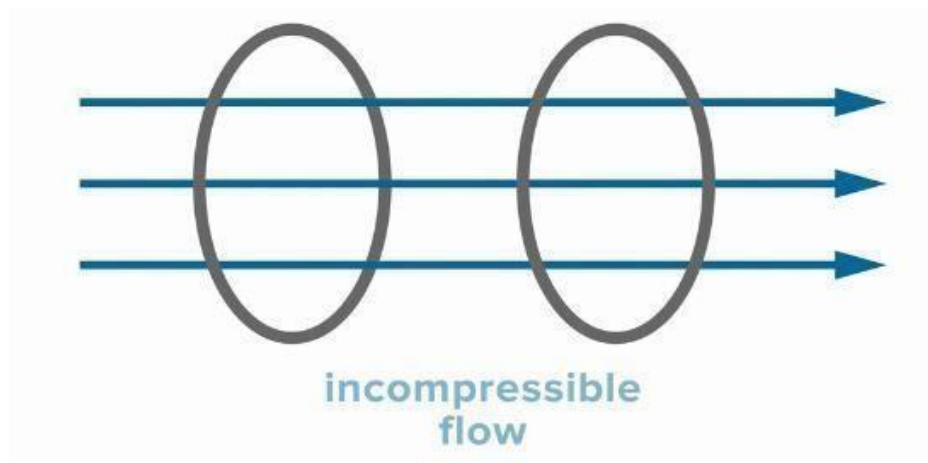


Fig:1.3 : Incompressible Flow

1.1.3 Laminar / Turbulent Flow:

Laminar Flow is a fundamental type of fluid motion characterized by smooth and orderly movement of a fluid, where adjacent layers or streamlines flow in parallel, without significant mixing or turbulent. In laminar flow, the fluid particles or molecules follow a well-defined and predictable path, maintaining their individual trajectories.

Laminar Flow is commonly observed in situations where the fluid velocity is relatively low, the flow path is smooth and unobstructed, and the fluid's viscosity is high.

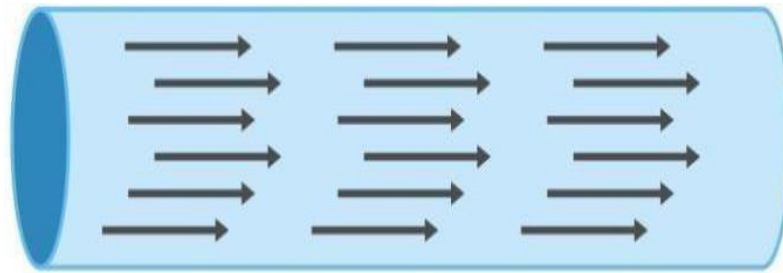


Fig:1.4 : Laminar Flow

Turbulent flow is a type of fluid flow characterized by chaotic, irregular, and random motion of fluid particles. In turbulent flow, adjacent layers or streamlines of the fluid mix together, creating a highly dynamic and complex flow pattern. Turbulent flow is commonly encountered in many natural and man-made scenarios, including river currents, ocean waves, airflows around vehicles, and water flowing through pipes with high velocities.

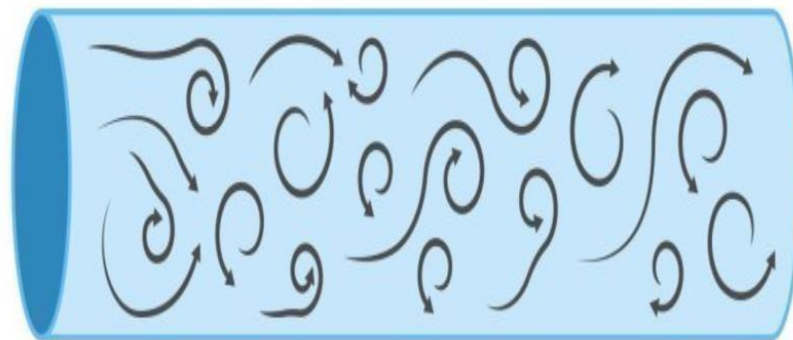


Fig:1.5 : Turbulent Flow

1.1.4 Viscous / Inviscid Flow:

Viscous flow is governed by the effects of fluid viscosity, resulting in frictional forces between adjacent fluid layers. Viscosity becomes significant at low speeds or in highly viscous fluids, causing flow resistance and boundary layer development. Understanding viscous effects is crucial for predicting drag, boundary layer behaviour and flow separation in aerodynamic application.

Inviscid flow refers to flow where viscosity is negligible, allowing for simplified analysis. Inviscid flow assumptions are often applied in idealized aerodynamic models to simplify calculations and focus on fundamental flow behaviours. While useful for conceptual understanding and initial design stages, inviscid flow models may not capture all real-world flow phenomena accurately.

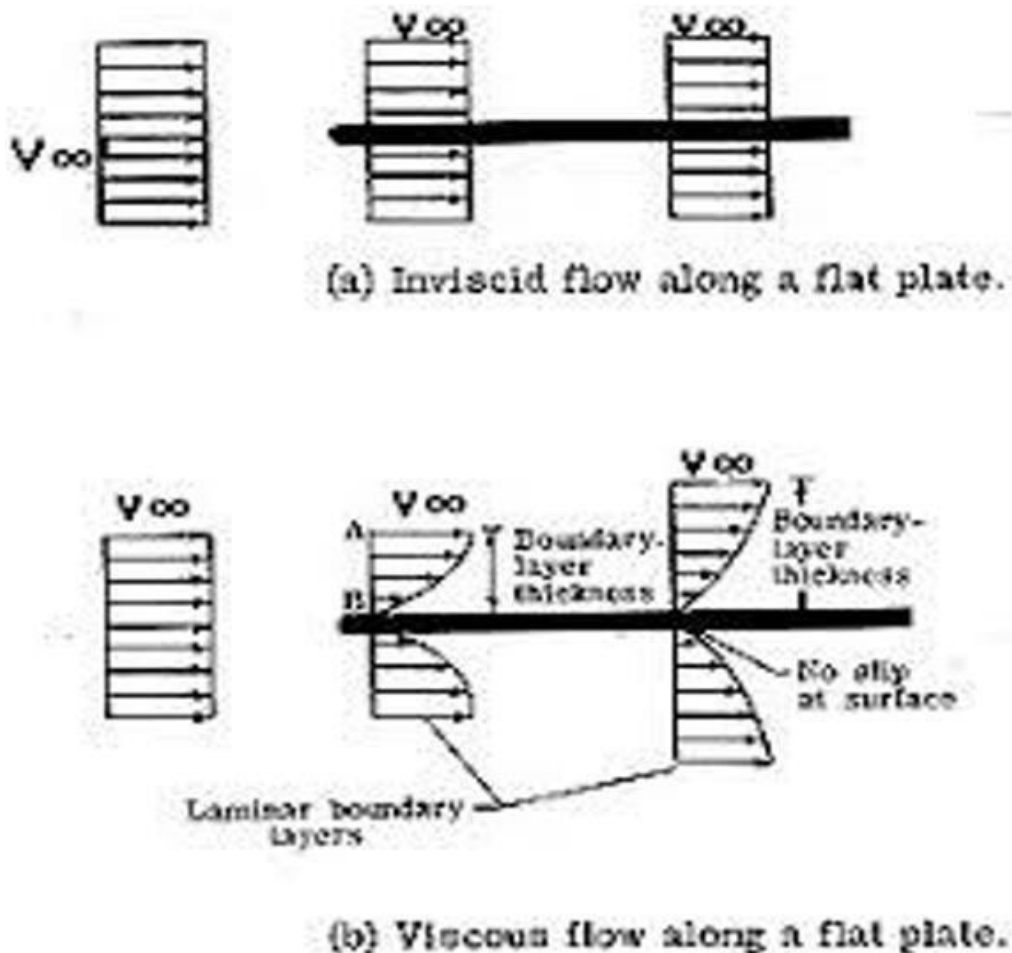


Fig:1.6 : Viscous and Inviscid Flow

1.1.5 Rotational / Irrotational Flows:

In rotational flow, fluid particles not only move but also rotate around local axes within the flow field, forming vortices or swirls. This rotation introduces angular momentum to the fluid to the fluid elements and is commonly observed in scenarios with sources of angular momentum or shear, such as vortex shedding behind obstacles.

Irrotational flow is characterized by the absence of fluid rotation within the flow field. Fluid particles move without inherent rotation, and the flow can be described using a scalar potential function. Irrotational flow is associated with flows dominated by pressure gradients rather than shear forces and is often seen in idealized potential flows and situations where viscous effects are negligible.

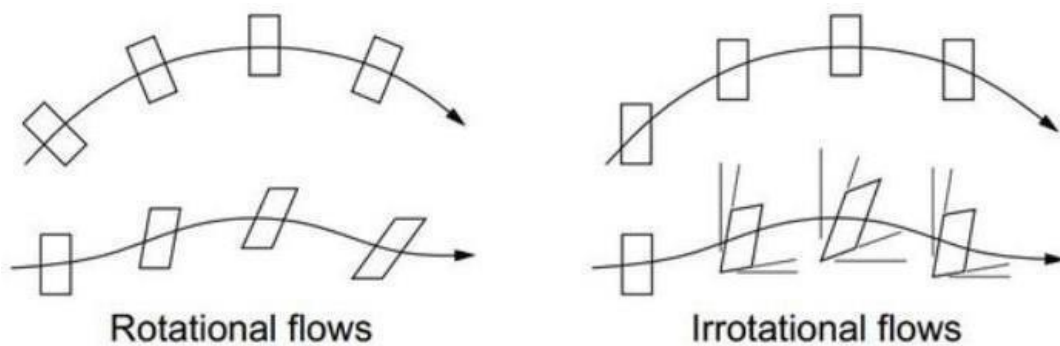


Fig:1.7 : Rotational and Irrotational Flows

1.2 REYNOLDS NUMBER:

Reynolds Number, often denoted as “Re”, is a dimensionless quantity used in fluid mechanics to characterize the flow of fluids, such as liquids and gases. The Reynolds number helps classify fluid flow regimes into two main categories: Laminar flow and turbulent flow.

Laminar flow occurs at Low Reynolds number (Re) i.e., $Re < 5 \times 10^5$ where the flow is predictable and follows linear patterns. Turbulent flow on the other hand occurs at High Reynolds number (Re) i.e., $Re > 5 \times 10^5$ where the flow is unpredictable and exhibits eddies and vortices.

The critical Transition between laminar and turbulent flow varies depending on the specific geometry and conditions of the fluid system. Engineers and scientists use the Reynolds number to predict and analyse the behaviour of fluids in various applications, such as in pipelines, aircraft design, and the study of natural phenomena like river flow and atmospheric patterns.

1.3 AERODYNAMIC FORCES ON AN AIRPLANE:

A Force maybe thought of as a push or pull in a specific direction. A force is a vector quantity since it has both direction and magnitude.

There are four forces that act on an aircraft:

- Weight
- Thrust
- Lift
- Drag

1.3.1 Weight:

Weight is a force that is always directed towards the centre of the earth. The magnitude of the weight depends on the mass of all the airplane parts, plus the amount of fuel, payload on board. In flight, the airplane rotates about the centre of gravity (CG).

1.3.2 Thrust:

To overcome the drag, airplanes use a propulsion system to generate a force called Thrust. The direction of the thrust force depends on how the engines are attached to the aircraft. The magnitude of the thrust depends on many factors associated with the propulsion system including the type of engine, the number of engines and the throttle settings.

1.3.3 Lift:

To overcome the weight force, airplanes generate an opposing force called lift. Lift is generated by the motion of the airplane through the air and is an aerodynamic force. Lift is directed perpendicular to the flight direction and the magnitude depends on the shape, size and velocity of the aircraft. Most of the Lift is generated by the wings. Aircraft lift acts through a single point called Centre of Pressure.

1.3.4 Drag:

Aerodynamic Drag, often referred to simply as “drag”, is a fundamental concept in fluid dynamics and aeronautics. It represents the resistive force encountered by an object as it moves through a fluid, such as air or water, at a certain velocity. This

force opposes the object's motion and results from the interaction between the object's shape and the fluid it is moving through.

Aerodynamic drag can be influenced by various factors, including an object's shape, surface roughness, and its interaction with the surrounding fluid. Optimizing the design of vehicles and other objects to minimize drag enhances their overall efficiency and performance.

Types of Drag:

- Parasite Drag
 1. Skin Friction Drag
 2. Form Drag
- Lift-Induced Drag
- Wave Drag

1.4 AERODYNAMIC EFFICIENCY:

Aircraft aerodynamic efficiency is a critical factor in the design and operation of airplanes. It refers to the ability of an aircraft to minimize air resistance or drag while maximizing its lift and overall performance. Achieving higher aerodynamic efficiency is essential for the economic and operational success of an aircraft.

High Aerodynamic efficiency is crucial for several reasons:

- Cost Effectiveness
- Fuel Efficiency
- Performance
- Operational Range
- Environmental Impact

1.5 VORTICES:

Vortices are swirling, rotational patterns of fluid motion that can be found in various natural and engineered systems. They are a fundamental phenomenon in fluid dynamics and play a significant role in understanding the behaviour of fluids, whether it's in the atmosphere, oceans, or engineering applications.

In aerodynamics, vortices are often associated with the generation of lift and drag in aircraft. Wingtip vortices, for example, are created when high-pressure air underneath an aircraft's wing moves around the wingtip and meets low-pressure air above the wing. These vortices are a crucial element in lift generation but also contribute to induced drag.

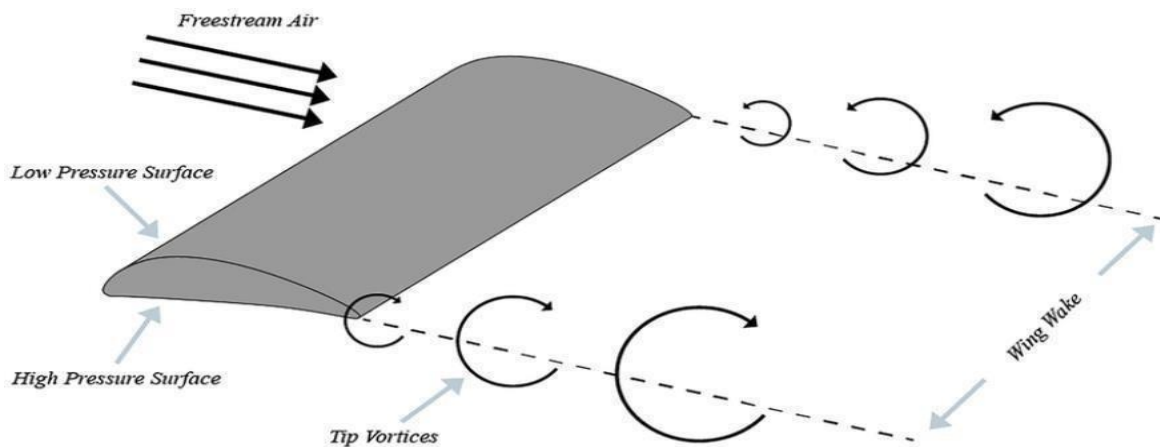


Fig:1.8 : Wingtip Vortices

1.6 BIOMIMETIC – DESIGN ENGINEERING:

1.6.1 Biomimetics:

Biomimetics is an interdisciplinary field in which principles from engineering are applied to the synthesis of materials, synthetic systems or machines that have functions that mimic biological processes. Biomimicry is about valuing nature for what we can learn, and not for what we can extract, harvest or domesticate.

Biomimicry is the practice of applying lessons from nature to the invention of healthier, more sustainable technologies for people. Biomimetic designers focus on understanding, learning from, and emulating the strategies used by living things, with the intention of creating designs and technologies that are sustainable.

With biomimicry, we can develop new products, processes, and systems, or improve existing designs. It can help us to shift our perspective, see design problems and objectives differently, and uncover “new” solutions to difficult problems.

1.6.2 *Why learn from nature?*

We have the innate potential to create a world that is harmonious, regenerative and supports the well-being of all life. As a young species, we are fortunate enough to have guidance to help us rise to this challenge. Our planet-mates, the fantastic mesh work of plants, animals and microbes have done billions of years of research and development. By infusing biological strategies in design, we can transform sustainable innovation [1].

1.6.3 *Types of Biomimetics:*

Mimicking the form or shape is the process of studying and imitating biological structures found in nature to design and create new technologies, materials, or functions. This approach is inspired by nature's efficiency, adaptability, and sustainability. By closely observing how living organisms have evolved and adapted to their environments, scientists and engineers can develop innovative solutions for various applications.

Mimicking the process in biomimetics refers to emulating the methods and mechanisms found in biological systems to solve engineering or design challenges. This approach involves studying how living organisms perform certain functions, adapt to their environments, and solve complex problems, and then applying those insights to develop new technologies or processes.

Mimicking the eco-system in biomimetics involves emulating the interconnected relationships, processes, and functions found in natural ecosystems to design sustainable and efficient human-made systems. This approach goes beyond individual organisms or processes and focuses on creating holistic solutions that mimic the complexity and resilience of natural ecosystems.

1.6.4 Levels of Biomimetics:

At the organism level in biomimetics, the focus is on studying specific organisms and their biological features to inspire the design of products or systems. This approach involves examining how organisms have evolved unique adaptations to survive and thrive in their environment and then applying those principles to develop innovative designs

The leaves of lotus plants have micro – and nano structures that repel dirt and water, keeping the leaves clean. This “lotus effect” has been mimicked in coatings for various surfaces, such as building materials and textiles, to create self-cleaning and water-repellent properties.

At the behaviour level in biomimetics, the focus shifts from specific organisms to studying broader behaviours, processes, or systems observed in nature. This approach involves analysing how living organisms interact with their environment, communicate, solve problems, and adapt to changes. By understanding these behaviours, researchers can develop innovative processes or behaviours in human-made systems.

Robotics inspired from animal locomotion and behaviours, such as quadrupedal movement inspired by mammals or flying drones inspired from birds, aim to achieve greater agility, efficiency, and versatility in robotics applications like search and rescue, exploration, and industrial automation.

At the ecosystem level in biomimetics, the focus expands beyond individual organisms or behaviours to consider broader ecological systems and their interconnectedness. This approach involves applying principles from ecological systems to inform policies, strategies, and outcomes in human-made systems and societal frameworks.

Inspired by natural ecosystems’ ability to regenerate soils and support agricultural productivity, regenerative agriculture policies promote sustainable farming practices that enhance soil health, water conservation, and biodiversity while reducing chemical inputs and greenhouse gas emissions.

1.6.5 Elements Of Biomimetics:

Emulate is the scientific research-based practice of learning and replicating nature's forms, processes, and eco-systems to create more regenerative designs.

Ethos is the philosophy of understanding how life works and creating designs that continuously support and create conducive to life.

The concept that we are nature, and find value in connecting to our place or earth as a part of life's interconnected systems. (Re)connect as a practice encourages us to observe and spend time in nature understand how life works so that we may have a better "ethos" to "emulate" biological strategies in our design [5].

1.7 DESIGN:

Design is one of the very important phases of a development process where it may be a product, system, process or algorithm. It is often misunderstood as a concept. It is commonly seen as the process of making products look aesthetically pleasing or stylish. Design is the process of turning ideas into product that can satisfy the requirements of customer with application of logical principles.

Design is a multi-disciplinary process which usually involve three major phases viz conceptual design, system level design and detailed design of components, based on customer needs and technological research to convert raw materials into finished goods, capable of performing specific functions [14].

Design is a cyclic process and thus does not end with detailed design. Refinement of design is necessary, after the prototype / final product development and testing.

1.7.1 Design in General:

The products of design are all around us. Every man-made object we use and service or system we interact with, was designed by someone, whether they

considered themselves a designer. Objects and graphics are obvious examples of design, but design decisions play an important role in less tangible outcomes such as services and systems and the plans and policies that affect community life. In many ways these “invisible” designs have an even bigger impact on how we live and experience the world.

Since design decisions have such wide-reaching impacts, in recent decades the use of design methods and tools (sometimes called “design thinking”) has spread beyond the confines of the “traditional” design disciplines and is used as a process for innovative thinking among business people, educators, scientists, social workers, communities and many other. Dozens of domains and disciplines and specific design approaches exist today to help practitioners describe and organize the design process. Engineering design, human-centred design, user-centred design, and design thinking are a few that may be familiarized in general [12].

1.7.2 Design in Engineering:

Engineering Design is a discipline of engineering that focus on creation and transforming ideas and concepts into product definition that satisfies the customer requirements with applied engineering concepts. This deals specifically with solving problems through creating something that does not exist. The design process includes material selection and properties of materials which is used in analytical design process. Engineering design procedure is iterative process till it satisfies the analytical relationship with permissible stresses of materials. When engineering design process is used for development of any ‘product’, it is called a product design.

1.7.3 Phases of Design:

The need for development for a new product arises in two cases:

- Improvement of existing design
- Designing altogether new product

In such case the first step is to decide the concept by which the desired needs can be achieved. Process of development of concept using different available technologies to achieve the desired function is called conceptual design. The aim of the concept development is to achieve the basic/main function for which a customer would purchase the product.

The selection of the technology has a major impact on overall cost of production, its performance, reliability, durability, and maintainability.

Once the conceptual design is decided based on various parameters, a system level design is worked out. The system design helps in identifying different important assemblies, sub-assemblies and components that may be required for achieving the function. Till this stage the size and specifications of the components are not decided. A layout of the entire design is usually prepared indicating overall dimensions of each assembly and major components.

In detailed design, every component is identified and their exact specifications like thickness, length, width, diameter, size etc are decided. The specifications include the major dimensions and features of the components. The detailed design is usually based on the maximum load acting on the component but this may not be the situation in every case.

In analysis phase also known as numerical analysis where the entire design is examined by using CAE methods. The analysis phase is a very important stage in design because it gives important information such as failure, design performance, visual representation, etc. If any problem occurs in the analysis phase the design is directed back to preliminary design stage to rectify the mistakes.

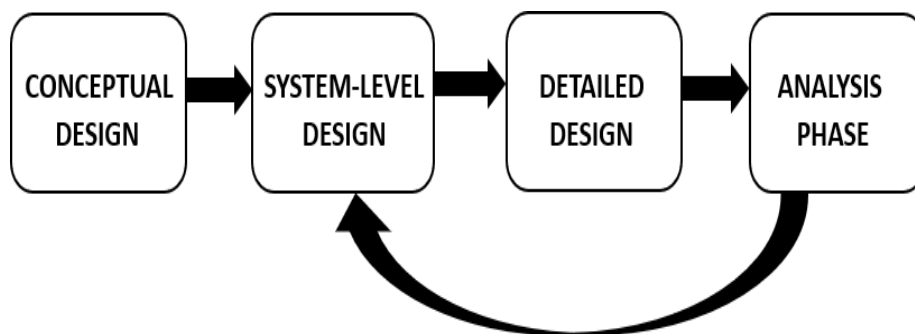


Fig:1.9 : Flow chart of phases of design.

1.7.4 Types of Design Techniques:

In sequential design, the engineering process follows a linear sequence of stages, where each stage depends on the completion of the previous one. This approach is often referred to as the “waterfall model” because progress flows in one direction, like water cascading down a waterfall. Sequential design is characterized by distinct phases such as requirements gathering, implementation, testing, and deployment, with each phase building upon the outcomes of the previous phase. Advantages of sequential design include clarity in process flow, easier tracking of progress, and well-defined milestones.

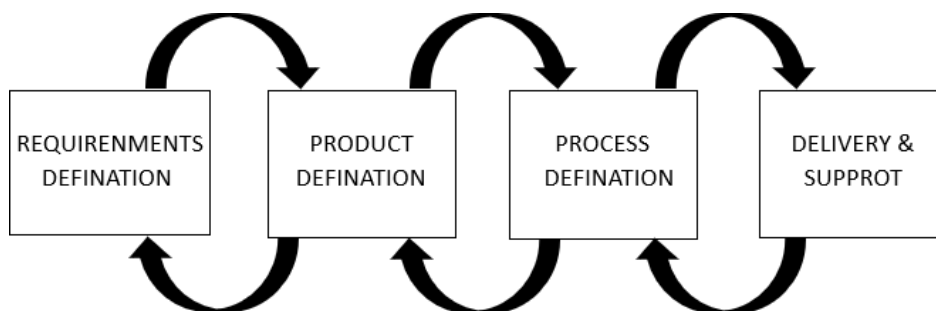


Fig:1.10: Flow chart of sequential design.

Concurrent design, also known as parallel design or simultaneous engineering, involves overlapping and parallel execution of different stages of the engineering process. Instead of waiting for one stage to be fully completed before starting the next, concurrent design allows multiple stages to process simultaneously. This approach emphasizes collaboration and integration among cross-functional teams, enabling faster product development cycles and reduced time to market. Advantages of concurrent design include faster product development, early identification and resolution of issues, and improved coordination among team members.

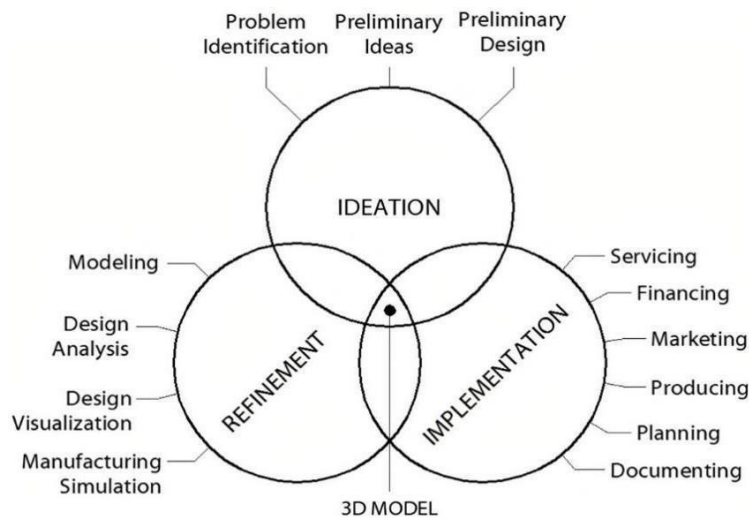


Fig:1.11 : Venn Diagram of Concurrent Design.

1.7.5 Biomimetic Design:

Biomimetic design is a scientific approach to sustainable design that involves studying and applying construction principle formed in natural environment and species. It is a process where nature inspires engineering to design a product. The science of engineering biomimetic design involves designing by imitating life in nature, as other organisms in nature have developed natural solutions like what we need today.

1.7.6 Biomimicry Design Spiral:

The biomimicry design spiral serves as a valuable framework for understanding the essential steps in successful biomimetic design. It guides the process of problem-solving or identifying design opportunities by encouraging practitioners to seek inspiration from biological models [17].

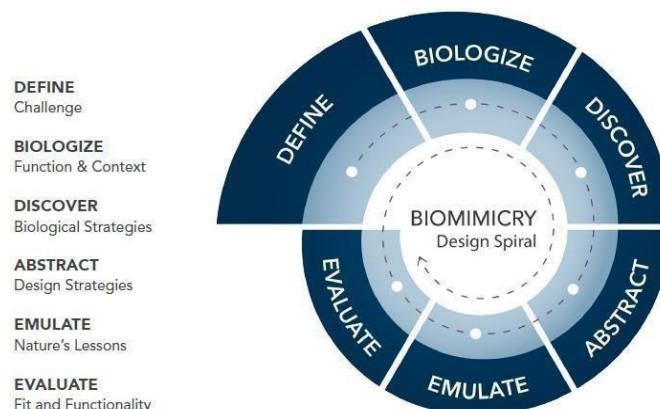


Fig:1.12 : Biomimicry Design Spiral.

- Precisely define the desired influence our design aims to achieve globally, along with the standards and limitations that will gauge its effectiveness.
- Examine the fundamental roles and environmental setting of the design solution that need consideration. Frame them using biological terminology to seek guidance from nature.
- Search for natural organisms and ecosystems facing similar functions and contexts as your design solution. Identify the biological strategies they employ to ensure their survival and thrive in their environment.
- Thoroughly examine the key characteristics or mechanisms that contribute to the success of biological strategies. Describe in simple terms your understanding of how these features work, using sketches to ensure clarity and accurate comprehension.
- Identify patterns and connections among the strategies discovered, focusing on the key insights that should guide the solutions. Generate design concepts informed by these strategies.
- Evaluate the design concepts to determine their alignment with the criteria and constraints of the design challenge and their compatibility with Earth's systems. Take into account technical and business model feasibility. Refine and revisit earlier steps as necessary to develop a viable solution.

1.7.7 Biomimicry Design Process:

1. Define the Challenge:

The first step in any design process is to define the problem or opportunity that design needs to address.



2. Biologize function and context:

The process of learning how to reframe the challenge into a biological context, to make it easier to find inspiration in nature.



3. Discover Biological Strategies:

The phase of learning where and how to look for biological models and strategies for inspiration.



4. Abstract Design Strategies:

This is the phase of learning how to translate biological strategies into design strategies, can be applied to the challenges.



5. Emulate Nature's Lessons:

The phase of applying insights gained from the abstract design strategies to the design challenges.



6. Evaluate the Fit and Function:

Exploring ways to test the biomimetic ideas and learning from what does not work in order to make the design better.

1.8 DERMAL DENTICLES:

Shark Skin dermal denticles have a unique diamond-shaped structure with tiny, overlapping scales that create a smooth texture relative to the motion on the shark's surface. It helps to reduce the hydrodynamic drag as the shark moves through the

water, enabling these animals to swim with impressive speed and efficiency. The denticles effectively break up the flow of water, reducing friction and turbulence. The unique design of shark denticles has inspired the development of biomimetic materials and technologies [23].

1.9 FIELD OF THE PROJECT:

The field of the project intervenes with biomimicry creature applied in the field of fluid dynamics, particularly to the fluid flow relative to a surface such as a lift generating wing. Moreover, this project related to the method of reducing the drag and the effects caused by the drag such as vortex and to enhance the performance of the wing.

CHAPTER – 2

LITERATURE SURVEY

P. Hamilton et al. (1965) investigated about the hydrostatic pressure under the shark's skin with varying swimming speed. The internal hydrostatic pressure was 7 to 14 kNm^{-2} under the skin of shark resting on tank floor. The pressure varied from 20 to 35 kNm^{-2} while swimming slowly and pressure rose to 200 kNm^{-2} while swimming at faster speeds and found out the pressure rose both on concave and convex sides of the shark.

M. Walsh et al. (1982) did an experimental study of low-speed turbulent boundary layer flow over longitudinally grooved surfaces (i.e., riblets). He obtained results with a highly accurate drag balance indicate that v-groove riblet surfaces can produce consistent net drag reductions as large as 8% provided the height and spacing of the grooves.

M. Walsh et al. (1984) explored riblet surfaces through experimentation in boundary layers with varied upstream conditions and Reynolds numbers. The drag reduction was determined to be contingent upon height and spacing when expressed in terms of law of wall variables.

D. Bechert et al. (1985) researched the drag reduction mechanisms by shark skin. Testing artificial surface with similar ridges in turbulent layer revealed 7% reduction in drag. While the operation of the scales as vortex generators doesn't diminish turbulent shear stress.

J. Magill et al. (1987) addressed the problem of controlling unsteady separation over aerodynamic surfaces using a closed-loop controller with surface embedded pneumatic actuators. He demonstrated the control of transient stall on a wing using pulsed vortex generator jets (PVGJs)

L. Broadley et al. (1997) investigated a study to examine the trailing edge flow separation mechanism. A parametric study using cropped delta vane vortex generators in a co-rating array was conducted to investigate the effect of vane chordwise position and orientation on the prevention of the trailing edge separation.

Through results and analysis, he obtained improvement in the performance of the vortex generator.

P. Hidalgo et al. (2008) conducted an experimentation of flow dynamics within and replicated shark skin equipped with bristles, aiming to understand their capability in reducing skin friction drag. The investigation revealed that the denticles present in shark skin may serve a hydrodynamic function by ensuring continuous flow attachment along the body. This mechanism could reduce pressure drag and the overall drag consequently.

A. Lang et al. (2009) conducted an experimentation for understanding the flow patterns generated within a model featuring bristled shark skin denticles. The findings revealed that the shark skin induced a cohesive arrangement of interconnected vortices embedded within the flow.

L. Mendelson et al. (2010) carried out the experiments to discern the turbulence augmentation achieved over a bristled shark skin model embedded inside a turbulent boundary layer. He obtained that the negative aspects of increased overall drag, as evidenced in the boundary layer profiles, would be minimized if only localized bristling were to occur thereby minimizing the surface areas of the bristled microgeometry.

L. Chamorro et al. (2011) investigated about the performance of riblets on wind turbine blades over a range of angle of attack. Wind Tunnel experiments were performed to quantify the drag reduction in a wind turbine airfoil using V-groove riblet structures.

A. Sareen et al. (2011) conducted an investigation to quantify drag reduction by employing riblet film to ascertain the most effective location for drag reduction. The results demonstrated notable drag reduction up to 5%.

D. Zhang et al. (2011) conducted a study using real biological shark skin as the basis. Comprehensive simulations of turbulent flow over the real shark skin were performed, and subsequent testing of the shark skin surface in a water tunnel revealed drag reduction.

C. Buttner et al. (2011) through experimentation, discovered that the riblet structure, composed of nickel super alloy, exhibited a reduction in wall shear stress up to 4.9% compared to conventional smooth surface. This substantiated the potential of engineered riblet to serve as effective drag reducing surface.

D. Zhang et al. (2011) conducted research into the high precision bio-replication of synthetic drag reducing shark skin. Drag reduction experiments demonstrated that the material exhibited outstanding synthetic drag reduction effectiveness, achieving a maximum drag-reduction rate up to 24.6%.

D. Zhao et al. (2012) explored the use of vacuum casting replication to reproduce micro-riblets found on shark skin for drag reduction. The investigation yielded maximum and minimum drag reduction rates of 18.6% and 9.7%.

G. Bixler et al. (2013) conducted an investigation into fluid drag reduction using microstructural surfaces inspired by shark-skin riblets. The study encompassed testing of sharkskin related surfaces in both open and closed channel flows. Results indicated that riblets exhibited enhanced drag reduction in turbulent flow compared to laminar flow. In open channel experiments, a maximum drag reduction of up to 10% was achieved, while in closed channel experiments, a maximum pressure drop reduction of up to 34% was observed.

K. Forster et al. (2014) conducted a numerical investigation focusing on vortex generators installed on heavily cambered wings. The study revealed the severity of stall experienced by wings equipped with ramp-type vortex generators primarily stems from feedback loop mechanism generated by the flow drawn through the generators by attached trailing flows.

Y. Ito et al. (2015) explored the impact of vortex generators (VGs) on transonic swept wings. The investigation revealed that co-rotating, blade-type VGs installed on moderately-swept transonic wings effectively mitigate shock-induced boundary-layer separation. Additionally, the study confirmed that the VGs applied to the 3D CRM (Common Research Model) are comparably efficient to those on the infinite-span wing with a moderate sweep angle

M. Garland et al. (2015) researched adaptive vortex generator structures aimed at reducing turbulent separation. The investigation focused on developing a

deployable compliant separation control system capable of forming from the continuous surface of an airfoil as needed, and reverting to normal conditions when not required.

A. Lang et al. (2015) conducted research on drag reduction using shark skin as inspiration. The investigation revealed that utilizing riblet film, especially considering potential clogging of the surface, resulted in a total decrease in drag of only 1-3%. Furthermore, it was found that separation control, in addition to reducing drag, could also enhance the manoeuvrability of vehicles.

A. Boomsma et al. (2016) Performed a direct numerical investigation of shark skin denticles within turbulent channel flow. Additionally, turbulent flow over drag-reducing scalloped riblets was simulated under similar conditions using the same numerical method for comparison. Despite the resemblance between denticles and riblets, both arrangements of shark skin led to an increase in total drag by 44-50%, whereas riblets reduced drag by 5%.

X. Pu et al. (2016) Explored the microstructures of individual denticles and assessed the mechanical properties of intact fresh shark skin comprising both epidermal and dermal layers. Findings indicate that biomimetic surfaces with riblet structures, when compared to flat surfaces used as control specimens, demonstrate a reduction in fluid flow drag ranging typically from 5% to 10%..

X. Pu et al. (2016) Researched the anti-biofouling and drag reduction properties of a biomimetic shark skin surface. Experimental investigations focused on drag reduction revealed that the microstructure of the prepared biomimetic shark skin surface significantly contributes to drag reduction. Results showed a maximum drag reduction rate of 12.5%, surpassing the corresponding maximum drag reduction rate of membrane material with a smooth surface.

G. Kibble et al. (2017) Performed an aerodynamic study on conformal vortex generators (CVGs). Quantitative image analysis revealed a reduction in shockwave fluctuations by 46% upon integrating CVGs, indicating a potential mechanism for drag reduction. The findings suggest that employing CVGs could potentially result in at least 4% fuel savings.

F. Afroz et al. (2017) Conducted an experimental investigation into laminar and turbulent boundary layer separation control using shark skin. The study revealed that under laminar conditions, shark skin induces an early transition to turbulence and diminishes the extent of laminar separation. In turbulent separation, the presence of shark skin reduces backflow and the size of the separation region. Additionally, under both flow conditions, shark skin delayed the point of separation compared to a smooth wall.

X. Pu et al. (2017) Conducted research on utilizing bio-replicated forming technologies to create a shark-skin surface. The study successfully replicated the biomimetic surface structure of shark skin morphology. The proposed PES (Polymer Electrospinning) and PEES (Precision Electrospinning) methods were found to be effective bio-replicated forming routes for simulating the microstructures of a shark-skin surface. Moreover, compared to the PES method, the PEES method exhibited greater precision in replicating the microstructure of a shark-skin surface.

Y. Fu et al. (2017) Conducted a study on marine drag reduction using shark skin-inspired riblet surfaces. The experiment revealed that increasing the interval between riblets led to a reduction in the wetted area, but also decreased the drag reduction effect of the riblet valleys

H. Takahashi et al. (2018) Conducted an evaluation study on skin friction drag reduction in turbulent boundary layers using riblets. The three-dimensional riblet surface, fabricated with a paint-based material, successfully reduced skin friction drag by approximately 6.3% at a location 67% downstream of the model leading edge, with a freestream velocity of 42 m/s.

A. Domel et al. (2018) Conducted research into shark-inspired designs aimed at enhancing aerodynamic performance. Significant efforts have focused on modifying airfoil surfaces to improve their aerodynamic characteristics. Drawing inspiration from the drag-reducing properties of shark skin's tooth-like denticles, the study achieved lift-to-drag ratio improvements comparable to the best-reported results for traditional low-profile vortex generators. Furthermore, these designs outperformed existing ones, particularly at low angles of attack, with enhancements reaching up to 323%.

H. Lijima et al. (2019) Researched skin friction drag reduction in turbulent boundary layer conditions over riblet surfaces. Flight test results regarding mean velocity demonstrated the effectiveness of a paint-riblet. Drag reduction rates obtained from various wind tunnels were approximately 5-6%, with the riblet reducing streamwise turbulence intensity in cases where drag was decreased.

W. Dai et al. (2019) Conducted experiments to explore drag reduction using 3D printed shark-skin-like surfaces. Findings indicated that the surface with scales oriented at 90 degrees exhibited the lowest viscosity drag, with a maximum viscosity reduction of 9%. A viscosity map, constructed using fluid dynamics principles, highlighted that the drag reduction effect of shark-skin-like surfaces was attributable to the low velocity gradient.

H. Chen et al. (2020) Conducted a study on the aeroelastic interactions and trajectory selection of vortex gusts impacting airfoils. The comparison between the numerical model and experimental measurements of vortex gusts over stationary airfoils underscored the suitability of the point-vortex model for inviscid vortex-airfoil interaction problems. This model proved particularly appropriate in scenarios where there was minimal decay in vortex strength, which contrasts with the more significant decay observed in predominantly viscous interactions during close encounters between vortex and airfoil.

S. Devey et al. (2020) Conducted an experimental analysis of passive bristling in air to facilitate shark-inspired separation control. Findings revealed that denticle bristling in air typically initiates at minimum dynamic pressures of around 2500 Pa. In contrast, bristling has been observed in parallel reversed flows in water at much lower dynamic pressures, as low as 300 Pa. The model successfully replicated the cavity Reynolds number of actual mako denticles.

S. Arunvinthan et al. (2021) Conducted experiments to evaluate the aerodynamic characteristics of Shark scale-based vortex generators (SSVGs) on a symmetrical airfoil. The study investigated the effectiveness of SSVGs at various chordwise locations (x/X) over the test airfoils, spanning a wide range of angles of attack (α) from 0 to 24 degrees in 3-degree increments, at a Reynolds number of 2.0×10^5 .

Results showed that incorporating the SSVG at a chordwise distance of $0.8C$ from the airfoil enhanced the lift coefficient (CL) by approximately 3.8%

E. Natarajan et al. (2021) Conducted a study on the hydrodynamic behavior of a biologically inspired bristled shark skin vortex generator for submarines. Numerical analysis and experiments demonstrated that deploying bristled shark skin vortex generators on the lateral side of a submarine significantly reduces drag during linear, yaw, and pitch movements. This reduction in drag coefficient is particularly pronounced at higher velocities. Additionally, during yaw and pitch movements, the fluid movement in the same direction as the body's rotation generates additional torque.

CHAPTER – 3

AIM AND SCOPE OF THE PRESENT INVESTIGATION

3.1 AIM:

- To investigate and implement the aerodynamic benefits using biomimetic design of shark skin denticles to enhance the efficiency of various engineering applications, ultimately to improve aerodynamic performance by reducing drag.
- This research presents a comprehensive study on the biomimetic design and development of novel shark foil, inspired by the intricate arrangement of dermal denticles observed in various shark species.
- The project aims to significantly enhance the aerodynamic efficiency. The primary focus of the project lies in pioneering a solution that optimizes the airflow by minimizing the drag.
- The project also aims to streamline the airflow dynamics, offering potential advancements aerodynamic performance, ultimately reducing energy consumption and improving overall aerodynamic functionality.

3.2 SCOPE OF THE PRESENT INVESTIGATION:

The application of Biomimetic design and development of the shark denticles has a major scope in the aviation Industry. The device is suitable for all incompressible flow fluid dynamics applications.

The device when attached in any region in any fluid dynamic bodied tends to increase the near surface velocity at low Reynolds number flows. The device deals with the drag suppression that decreases the skin friction drag ultimately in all regions of low Reynolds number flows.

3.2.1 Aerospace Applications:

Shark denticle inspired designs can contribute to improved lift and manoeuvrability in various aerodynamic applications. These designs take advantage of the unique surface properties of shark skin to reduce drag and enhance lift.

- **Drag Reduction:** Shark denticle inspired designs help reduce aerodynamic drag on aircraft surfaces. By emulating the low-drag properties of shark skin, we can improve fuel efficiency and reduce operating costs. Reduced drag allows for faster speeds and better.
- **Improved Lift:** Shark skin biomimicry enhances the lift generated by the wings of aircraft, improving take-off, landing and overall flight performance. This is particularly important in the aviation industry for achieving optimal control and efficiency,
- **Fuel Efficiency:** One of the key challenges in the aviation industry is to improve fuel efficiency and reduce emissions. Biomimetic designs inspired by shark denticles can significantly contribute to these goals by lowering fuel consumption and greenhouse gas emissions.
- **Environmental Impact:** By decreasing fuel consumption and emissions, shark skin denticle biomimicry supports the aviation industry's efforts to reduce its environmental impact. It aligns with the industry's sustainability goals and helps address environmental concerns.
- **Versatility:** Biomimetic designs can be applied to a wide range of aircrafts such as commercial aircrafts, military aircraft, and UAVs. This versatility ensures that the benefits of shark skin-Inspired designs can be realized across the entire aerospace spectrum.

Hence the investigation will provide valuable insights into the underlying concept of total drag reduction, and improvisation of aerodynamic performance of the aircraft, increasing the velocity with the suction of air as a push concept as the additional advantage, converting the turbulent flow of a fluid into a laminar flow which is the first of kind in aviation.

CHAPTER – 4

METHODOLOGY OF DESIGN, COMPUTATION AND EXPERIMENTAL ANALYSIS

4.1 METHODOLOGY:

The methodology of this project will involve in experimental testing in a wind tunnel to validate the numerical simulations and optimize the design of the shark denticle. The expected outcome of this project is focussed on the application of the shark skin denticle through biomimicry in the aviation industry, which holds the potential for substantial benefits and contributions to the field. The project's ultimate goal is to implement biomimetic designs inspired by shark denticles to enhance aerodynamic efficiency, reduce fuel consumption, and improve the overall performance of the aircraft. One of the primary outcomes is the development of the innovative biomimetic designs that can significantly reduce aerodynamic drag and increase lift. Thus, these designs have the potential to revolutionize the aviation industry by making the aircraft more fuel efficient, leading to cost savings and reduce environmental impacts. This involves in designing, computational and experimental analysis of the shark denticle on the wing.

4.1.1 Step – 1: Biomimetic approach to designing the shark denticle:

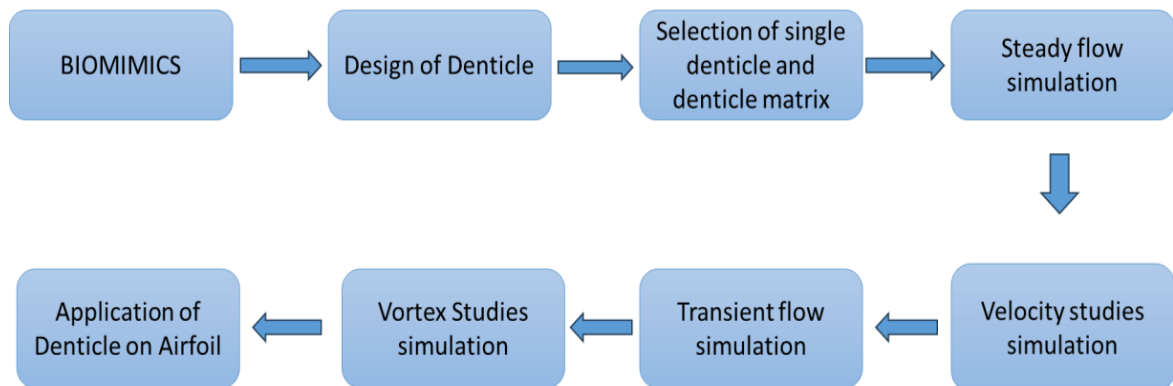


Fig:4.1 : Step – 1: Biomimetic Design of Shark denticle

4.1.1.1 Biomimetics:

Biomimetics, also known as biomimicry, represents a groundbreaking approach that taps into the wealth of nature's ingenuity to tackle complex human challenges. This method isn't merely about problem-solving, it's a visionary journey towards sustainable solutions by mirroring the tried-and-tested patterns and strategies found in the natural world. It involves a thorough examination of natural systems, processes, and organisms, seeking inspiration to drive innovation across diverse fields of engineering and design.

One captivating example lies in the emulation of sharks, renowned for their unparalleled hydrodynamic efficiency and remarkable speed, reaching up to 6 meters per second on average. This exceptional agility is owned to the composition of their skin – a sophisticated geometric structure that blankets their entire bodies. As fluid, such as water, interacts with this intricate surface by experiencing a suctioning effect which helps to push the shark faster, and it undergoes a transformative process, transitioning from turbulent to laminar flow. This phenomenon not only propels the shark forward but also holds immense potential for application in the aviation industry.

By integrating principles inspired by the natural world into aviation, there's a promise of enhanced efficiency, performance, and notable, reduced operational costs [27].

4.1.1.2 Design of Shark Skin Denticle:

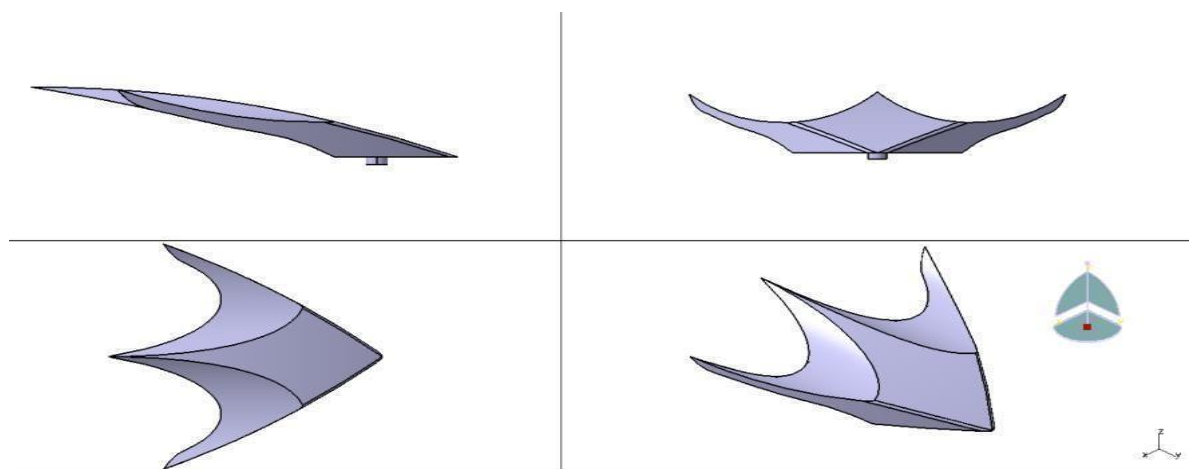


Fig:4.2 : Bio-inspired design of Shark Skin Denticle

Exploring the realm of Shark denticles unveils a multifaceted tapestry of research, delving into the intricate nuances and extraordinary properties of these specialized structures adorning the skin of sharks. Known interchangeably as dermal denticles or placoid scales, shark denticles represent a captivating field of study, encompassing a spectrum of facets ranging from their structural morphology to their distinctive surface texture adorned with minuscule V-shaped ridges.

These remarkable features extend beyond mere aesthetic allure, as they wield profound aerodynamic and hydrodynamic implications. Indeed, the design intricacies of shark denticles have piqued the interest of biomimetic enthusiasts seeking inspiration from nature's ingenuity.

In the pursuit of biomimetic innovation, our focus has converged upon the remarkable architecture of shark denticles as a blueprint for enhancing aircraft wing efficiency. By emulating the structure and functionality of these natural marvels, we aim to revolutionize the aerodynamic performance of aircraft. Our endeavour is driven by the recognition that integrating shark-denticle-inspired designs into the wing area holds the potential to substantially mitigate total drag, thereby optimizing aerodynamic efficiencies and advancing the forefront of aviation industry.

This approach underscores the profound impact of biomimetics, where nature's evolutionary solutions serve as catalysts for transformative technological advancements.

The denticle carries a notch fitted to the attachment region '1' of any hydro / aerodynamic structures. The embodiment carries leading edge flatter curved body which provides a single stagnation point closer to the part '1'. Near to attachment region, the trailing edge curved body '10' separates the flow closer to the surface. The sharp delta shaped frontal part of the device, the nose droop '3' splits the flow into two guideways of leading-edge separator '4' adjacent to it and the flow over the device up to trailing edge central spike '7'.

The embodiment '7' droops with the deflection angle which diversifies the boundary layer streamlines and swirl rate increases with formation of vortex in clockwise direction. The flow split in two guideways of part '4' flows up to left hand '8' and right-hand edge spikes '9' by '11'. The embodiment '8' and '9' droops at an angle where

the swirl rate increases with the formation of the tip vortex in the anti-clockwise direction.

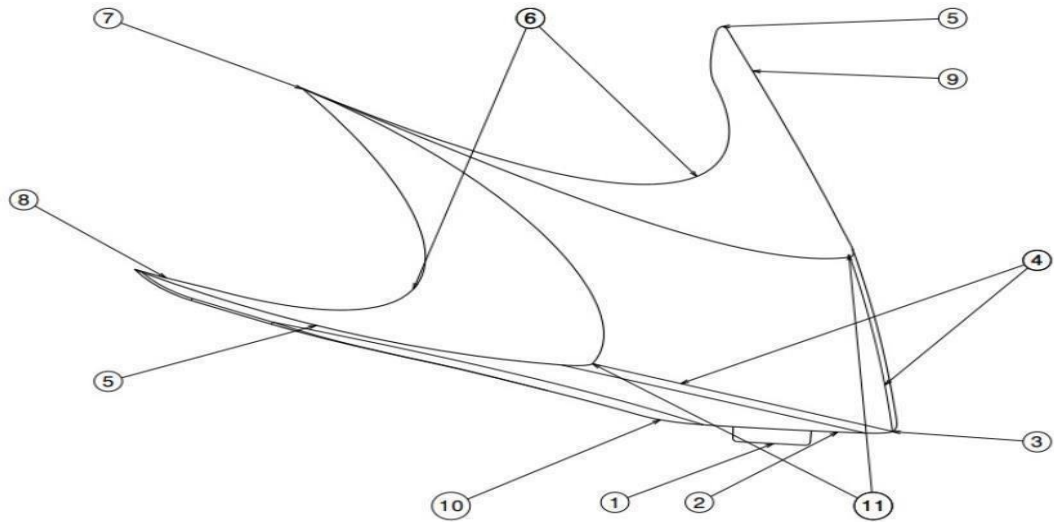


Fig:4.3 : Illustration of the designed Denticle.

The down-washer '6' is located in between the trailing edge spikes connecting '7' & '8' and '8' & '9'. This embodiment '6' downwashes i.e., changes the direction of the deflected air in which the lift coefficient depends on downwash generated. Trailing edge vortex deflector '5' started from embodiment '3-7' futuristically provided for increasing the downwash and momentum of the fluid to continue behind the down-washer '6'. The embodiment '5' also pull down the skin friction effect and vortex pairing emerge behind the '6'

The reattached point of pairing vertices made near to the surface of the wing adjacent to the embodiment '7' and creates a momentum-to-momentum transfer near to the wall. Thus, the momentum to momentum of fluid behind the down-washer holds the vortices from embodiment '7,8 & 9' downward provided possible momentum transfer to the fluid which decreases the skin friction coefficient of the wall, automatically leading to the reduction of the total drag.

4.1.1.3 Selection of Single Denticle and denticle matrix:

Selecting a single efficient denticle and its matrix is an iterative process that involves deep understanding and study of shark denticle and its types, physics behind it and previous researches. This leads to conclusion of the right species in which further experiments and studies can be conducted. In this project a hybrid design of the

denticle has been designed by combining two different species of shark which improves both speed and efficiency.

4.1.1.4 Steady Flow Simulations:

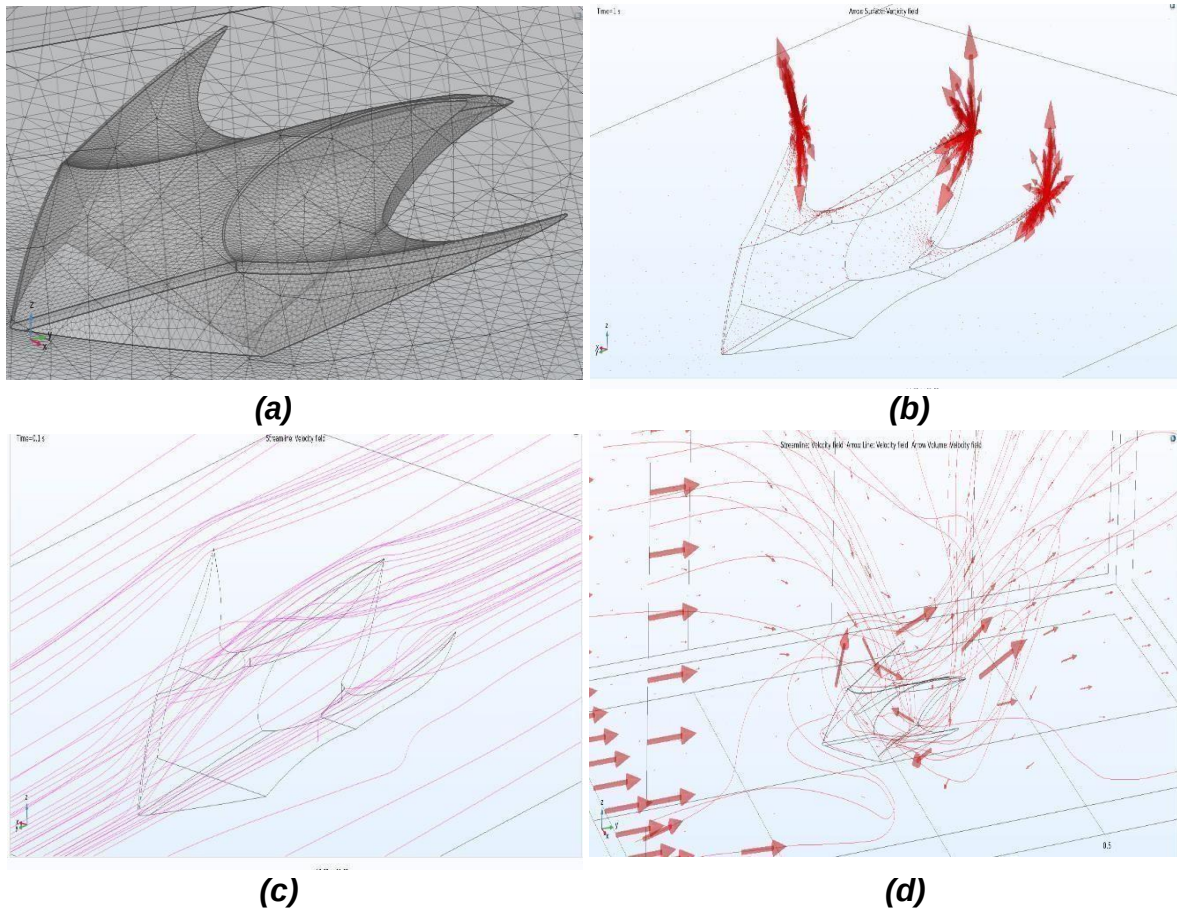


Fig:4.4 (a), (b), (c) & (d) : Steady state flow simulation process

This project uses the computational power of the COMSOL Multiphysics Computational Fluid Dynamics (CFD) module to meticulously analyse the intricate fluid dynamics surrounding a meticulously crafted model of dermal denticles, inspired by a hybrid passive geometric structure amalgamated from two distinct species of sharks.

Employing the k-epsilon laminar and turbulence model, our simulation endeavours to emulate the complex fluid flow phenomena observed in the natural environment inhabited by sharks. For the inlet conditions, we prescribe a fully developed, turbulent profile with a mean velocity of 5 m/s, carefully calibrated to mirror the swimming velocity characteristic of sharks.

At this nascent stage of model development, our primary focus centres on elucidating the intricate crown structure adorning the summits of the denticles. The crown structures hold the key to unlocking the potential for mitigating skin friction drag – a pivotal factor in enhancing overall aerodynamic efficiency.

4.1.1.5 Flow Simulation:

Meshing this model poses many interesting challenges; one of which being the sheer number of mesh elements required to mesh the denticles themselves. To achieve meshing, a user-defined, slightly coarser than desired, mesh was employed. Using the desired, Built-in, physics controlled, normal mesh was employed.

The results show that the model is able to predict the fluid flow and obtain good agreement with experimental studies of the same flow phenomenon. The velocity indicated the presence of counter-rotating vortices in the flow. Continuing the work of this project would include looking at possibilities to simulate using the low Reynolds K-epsilon model to get more correct picture of the interesting boundary layer properties of this fluid flow.

4.1.1.6 Velocity study and simulations

The meticulously designed denticle is seamlessly integrated into the COMSOL fluid solver, where precise flow conditions are prescribed. With the fluid velocity set at a representative 5m/s, the model captures the transition from vortex-dominated flow to laminar flow. This pivotal observation underscores the remarkable efficacy of the geometric structure in attenuating turbulence, heralding a paradigm shift in fluid dynamics.

The implications of this discovery reverberate across a myriad of disciplines, with far-reaching ramifications for fields such as aerodynamics, hydrodynamics, and heat transfer. By mitigating turbulence and promoting laminar flow, our findings promise to catalyse advancements in the design of vehicles, pumps, pipelines and myriad other systems reliant on optimal fluid flow dynamics.

In essence, this breakthrough holds the promise of unlocking more streamlined and efficient designs, poised to revolutionize industries and propel technologies innovation to unprecedented heights.

4.1.2 Step – 2: Design and Analysis of the Airfoil:

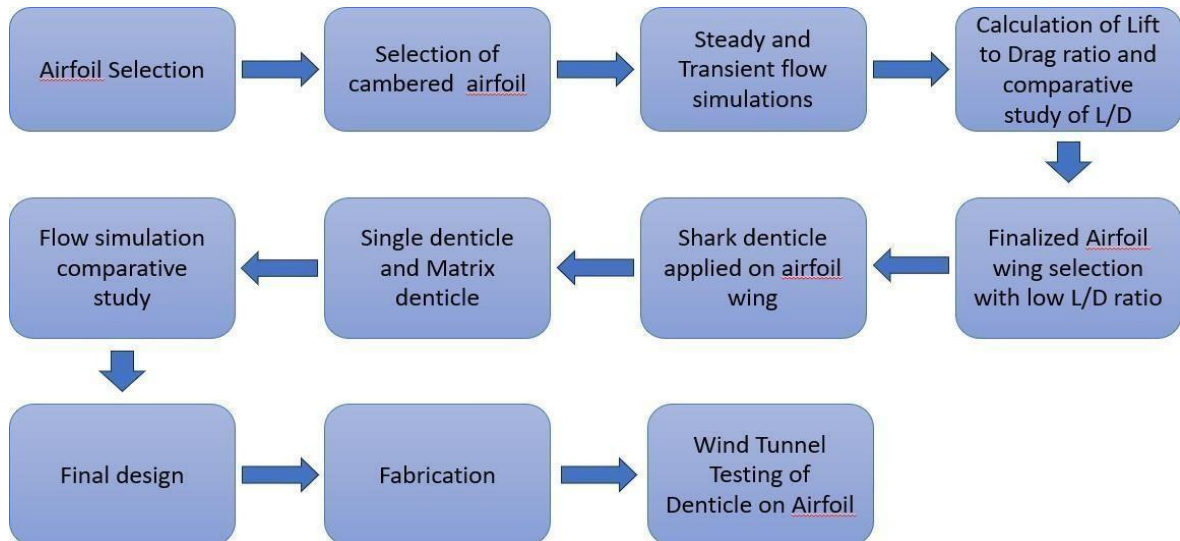


Fig:4.5 : Step – 2: Design and Analysis of the Airfoil

4.1.2.1 Airfoil Selection and analysis:

In aviation, airfoils, which are streamlined shapes, are crucial for generating lift and maintaining aircraft stability during flight. This project's main focus is to identify the airfoils with poor aerodynamic performance i.e., specifically those with low lift-to-drag (L/D) ratio. The aviation industry typically selects airfoils based on the higher L/D ratio for better aerodynamic performance. If the L/D is higher, it means the Lift produced is more than the drag and hence it is efficient, but if it is lower, the drag is produced more than the lift and hence it is not advisable to use the airfoil or the wing of that series. Our project aims to enhance the aircraft's performance and reduce the total drag. To achieve this, we analysed various airfoils, such as NACA 3413, 6410 and 8310, with a focus on identifying their stall angles which are poor in aerodynamic performance. With the entry velocity of 250 m/s in the ANSYS Fluent software, we determined the stall angles of these airfoils.

Following Aviation Safety Standards, we ensured that the airfoils stalled at a minimum angle of 15 degrees. We select airfoils with stall angles below 15 degrees, which indicates that they produce increased drag as the angle of attack increases.

With the completion of analysis, we obtained the results as follows:

- i) For NACA 3413 – The Stall angle was observed at 13.2 degrees of Angle of Attack (α).

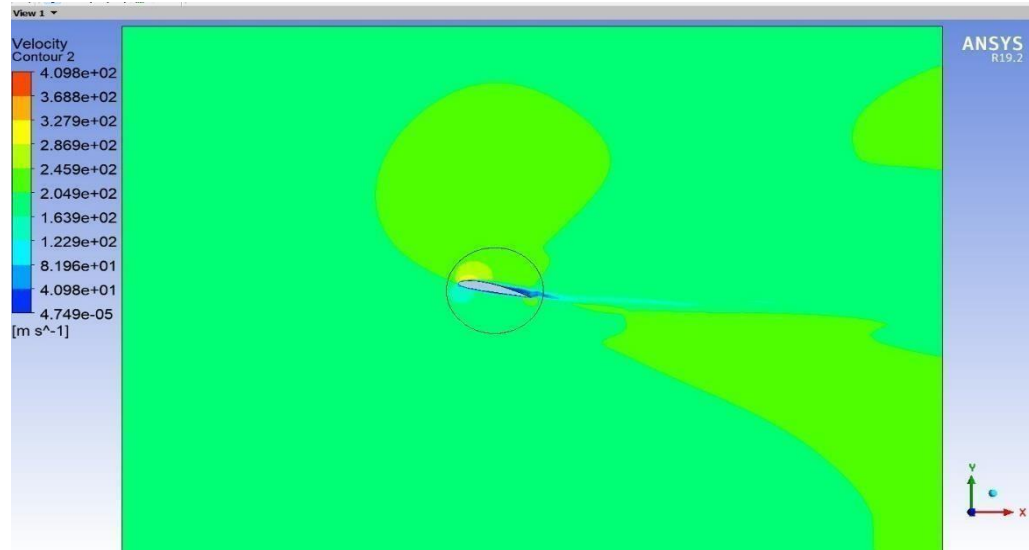


Fig:4.6 : NACA 3413 – Stall Angle 13.2 degrees

- ii) For NACA 8310 – The Stall angle was observed at 12.3 degrees of Angle of Attack (α).

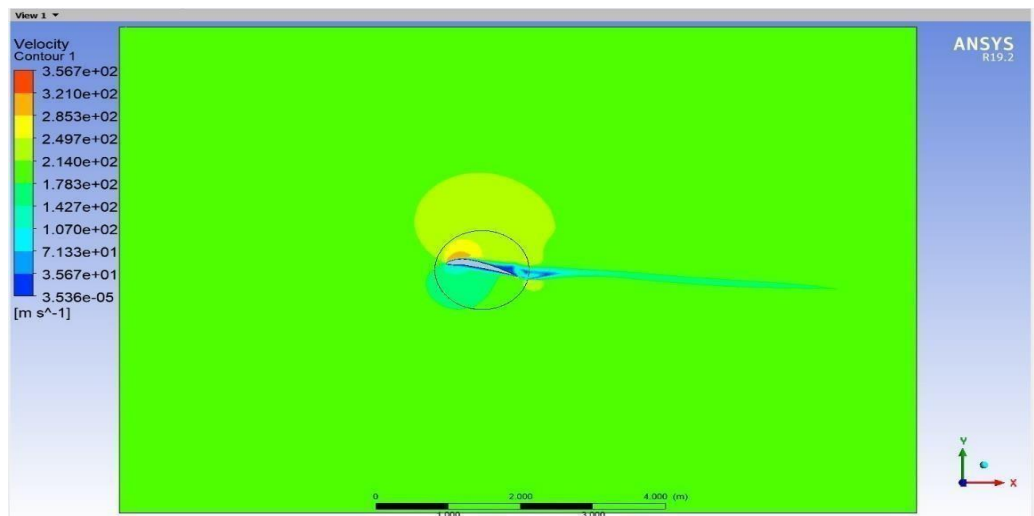


Fig:4.7 : NACA 8310 – Stall Angle 12.3 degrees

The stall angle is calculated by the C_L and C_D of the airfoil produced in different Angle of Attacks.

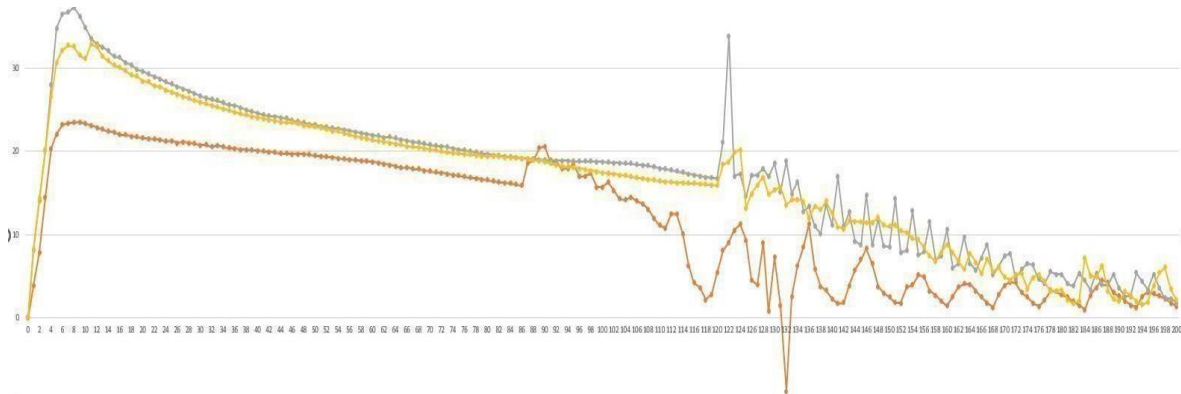


Fig:4.8 : Comparison plot of NACA 3413, 6410 and 8310

The graph between the Angle of Attack (α) and the L/D ration has been plotted and with reference to the stall angles produced by the airfoils, NACA 8310 airfoil has most low Lift-to-Drag ratio i.e., the poorest aerodynamic performing airfoil that produced the stall angle earlier than the other two airfoils at 12.3 degrees of Angle of Attack which 2.7 degrees less than the 15 degrees of angle specified by the aviation safety standards.

4.1.3 Step – 3: Analysis of the Shark denticle applied on the Wing:

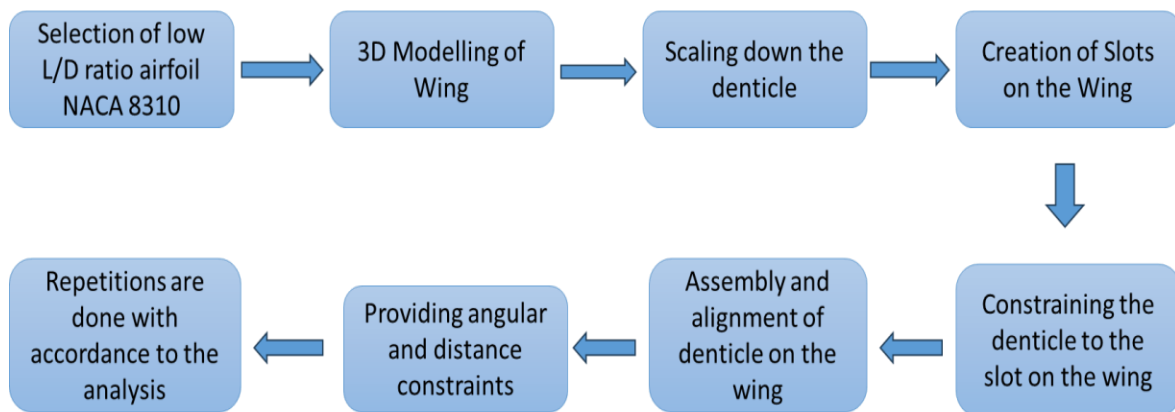


Fig:4.9 : Step – 3: Denticle on Wing

The application of shark denticles on the wing plays a crucial role in the reduction of boundary layer separation and the promotion of laminar flow. Denticles create tiny, vorticity-generating channels in the gaps between each denticles, which

energize the boundary layer and prevent flow separation. This, in turn, minimize drag and allows the aircraft to maintain higher speeds with less fuel consumption.

Furthermore, the scale-like nature of denticles provides a structured surface that can mitigate the onset of turbulent airflow, which is a primary cause of drag. By imitating this natural adaptation, aircraft wings can attain smoother laminar airflow, thus enhancing their aerodynamic performance. This concept holds promise for improving the fuel efficiency and manoeuvrability of aircraft, which could translate into reduced operational costs and environmental benefits.

As our aim of the project is to improve the aerodynamic performance of aircraft with the implementation of our designed shark denticle on the wing, and based on the results obtained from previous analysis, the NACA 8310 airfoil has been chosen as it has the low aerodynamic performance.

The airfoil is extruded as a wing and the 3D analysis has been carried out in ANSYS fluent. The analysis of the wing with denticle has been carried out in three ways:

- i) Wing without denticle
- ii) Wing with single denticle attached at 6.5 mm chord distance from the leading edge of the wing.
- iii) Wing with a row full of denticles attached at 6.5 mm of chord distance from the leading edge of the wing.

The analysis of denticle on wing shows the true potential of the denticle in the drag reduction by promoting the laminar flow. Additionally, another added feature of the denticle when attaching it on the wing is that, the denticle not only reduces the drag but also induces the velocity with the help of recirculation behind the denticle.

- i) Wing without Denticle:

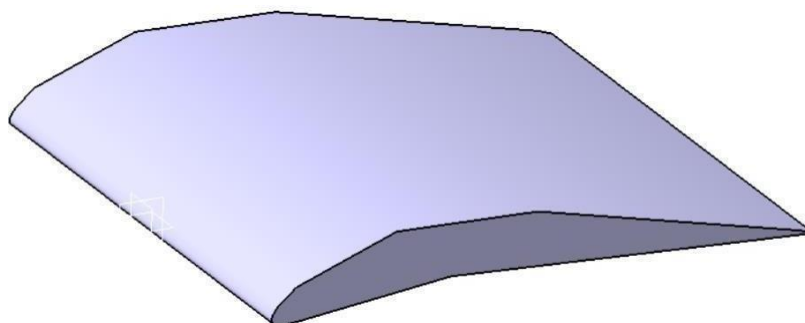


Fig:4.10 : NACA 8310 Wing without Denticle

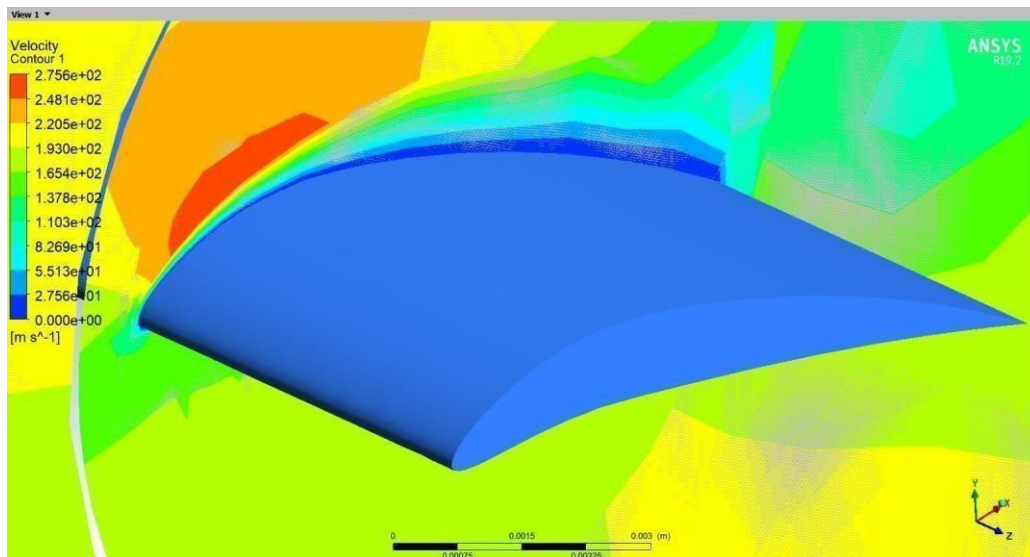


Fig:4.11 : Stall Angle – 12.3 degrees

The wing has been analysed without denticle initially with an entry velocity of 250 m/s and observed that the flow separation increases with 12 degrees of Angle of Attack from 6.5 mm chord and it is also observed that the distance of the reattachment region is proportional to the flow separation region. Hence, the drag increases with the increase in distance of reattachment region and Angle of attack. Therefore, the stall angle was produced at 12.3 degree of Angle of Attack as observed in 2D analysis.

- ii) Wing with single denticle attached at 6.5 mm chord distance from the Leading edge of the wing:

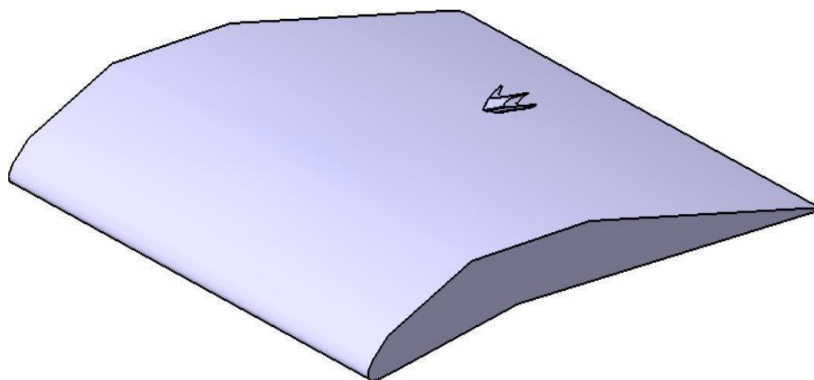


Fig:4.12 : Wing with Single Denticle

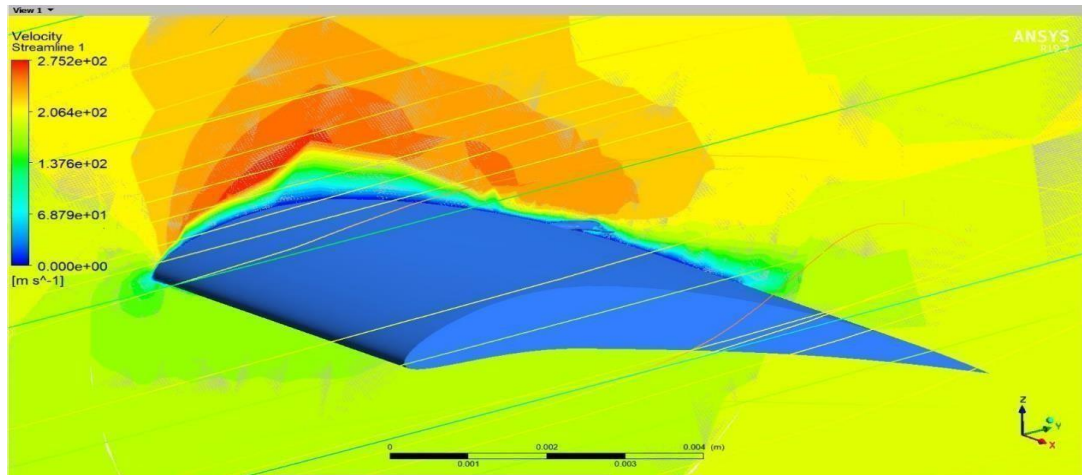


Fig:4.13 : Flow over the wing with single denticle

The addition of the denticle on the wing, reduces the drag in such a way that, the reattachment areas as observed has been reduced as compared to the analysis done without denticle. When the reattachment point reduces, the amount of skin friction drag can be reduced and paves way to reduce the total drag. When a single denticle is attached on the wing, the stall angle has been increased from 12.3 degrees to 25 degrees.

The upstream flow of the air is split into two at the leading edge of the wing. The flow detaches at 0.65 C due to the flow separation without the denticle. When the denticle is attached, the denticle downwashes the flow and keeps the flow attached over the surface. The downwash flow behind the denticle is pulled by the upstream flow due to the highly looped pairing of Clock-Wise (CW) and Counter Clock-Wise (CCW) vortices. This formation helps the wing to suppress the skin friction drag but the induced drag increases due to the tip vortices.

- iii) Wing with a row full of denticles attached at 6.5 mm of chord distance from the Leading Edge of the wing:

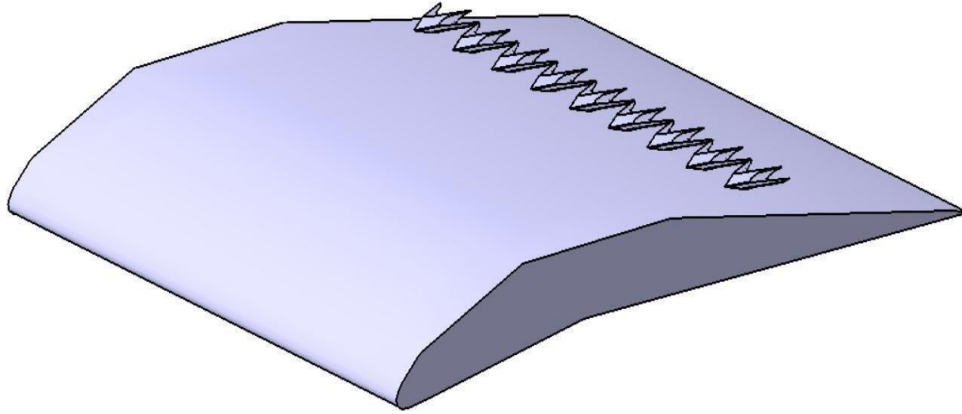


Fig:4.14 : Assembly of Denticles in a row on the wing.

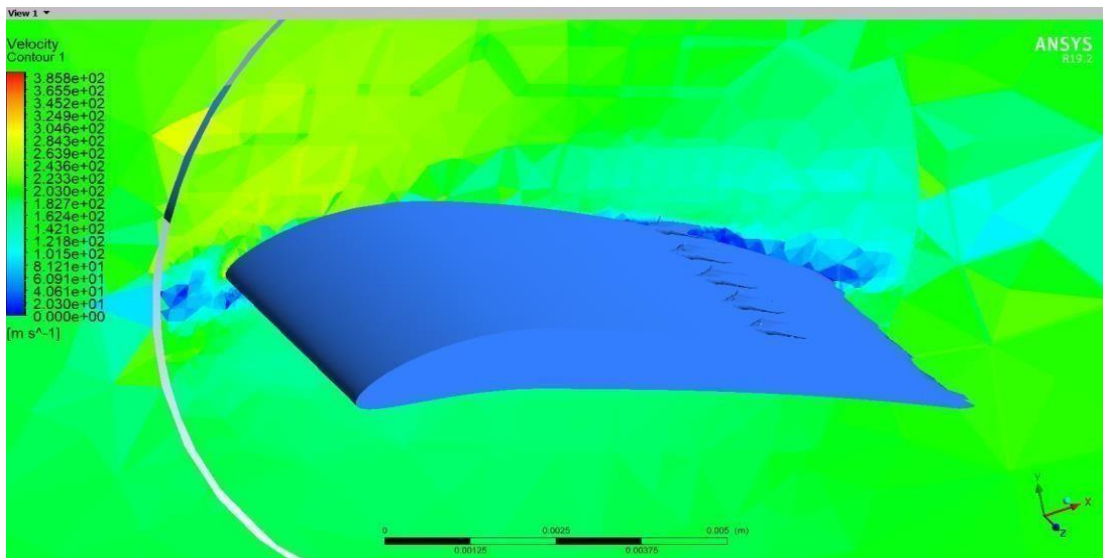


Fig:4.15 : Flow over the wing with a row full of denticles

With the application of denticles over a complete row arranged at 6.5 mm of chord from the leading edge of the wing, has significantly improved the aerodynamic performance of the wing. With the reduction of reattachment area, the drag has been reduced and the stall angle has been improved from 12.3 degrees to 20 degrees.

In the row wise arrangement, the denticles are arranged with equal spaces to each other with the width of the single device. Since the denticles are attached

in a row at 65% of chord from the leading edge, the row arrangement creates vortex pairs that produce downwash and reduces the skin friction drag which will continue across the span. The downwash elements of paired vortices looped near to the trailing edge, increases the moment CW – CCW – CW at tip to tip.

Hence the surface velocity has been improved by showing significant flow of the air as the fluid medium to be improved, which is proven by the simulation in COMSOL Multiphysics and ANSYS Fluent. As well as creating a low-pressure spot between each denticles creates a vacuum effect which sucks the air from the high-pressure region that induces the velocity by experiencing a pushing effect and the conversion of the vortices created to laminar flow improves the performance of this passive geometric structure.

4.1.4 Step – 4: Experimental Analysis:

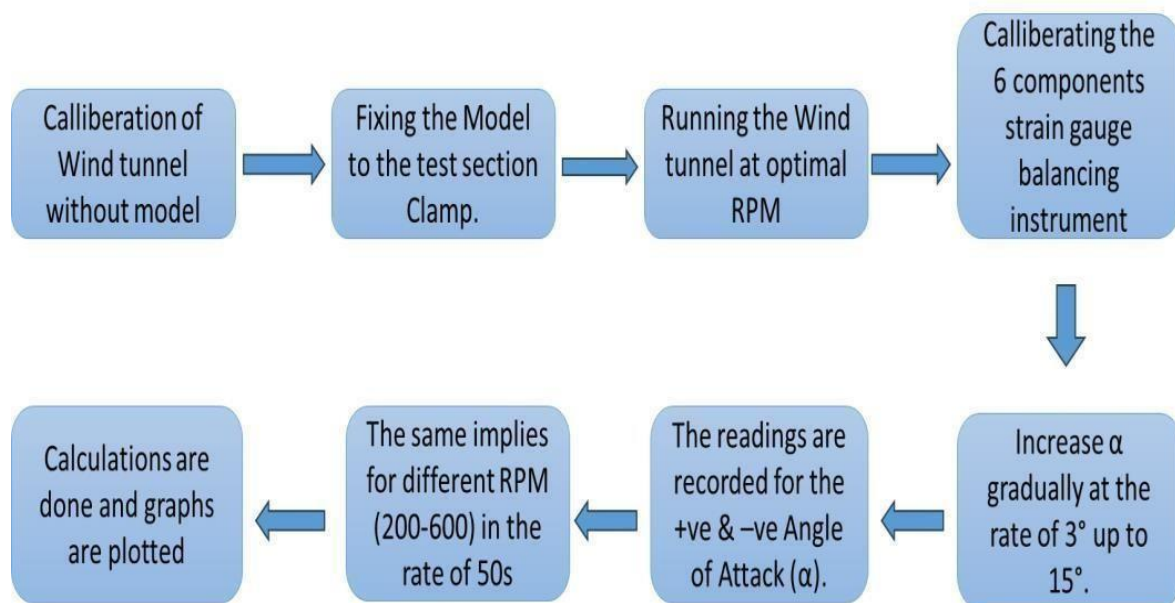


Fig:4.16 : Step – 4: Experimental Analysis

The experimental analysis begins with the calibration of the wind tunnel, ensuring its accuracy and reliability even without a model present. Once calibrated, the model is securely fixed to the test section clamp, ensuring stability and consistency throughout the experiment. The wind tunnel is then operated at its optimal RPM to generate the desired airflow conditions.

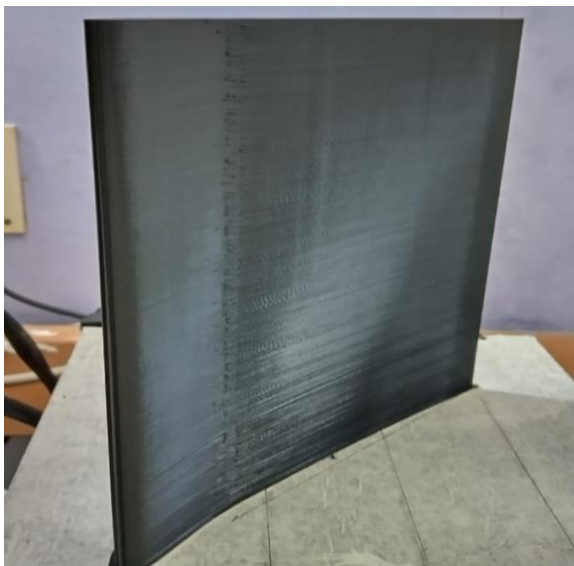
Subsequently, the six-component strain gauge balancing instrument is calibrated to ensure precise measurement of forces acting on the model. This step is crucial for accurate data acquisition during the experiment.

With the setup prepared, the angle of attack (α) is systematically increased from 0 to 15 degrees in increments of 3 degrees. Readings are recorded for both positive and negative angles of attack to capture the full range of aerodynamic behaviour.

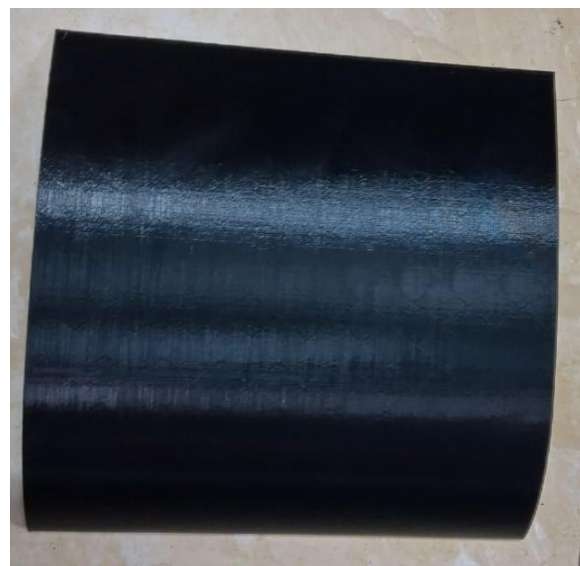
Furthermore, variations in RPM from 200 to 600 are explored, adjusting in increments of 50 RPM. This range allows for the examination of how different airflow velocities affect the model's aerodynamic characteristics.

Following the data collection, thorough calculations are conducted to analyse the results, considering the various parameters involved. Graphs are then plotted to visualize trends and patterns, aiding in the interpretation of experimental findings.

Overall, this comprehensive methodology ensures a systematic approach to experimental analysis, facilitating accurate measurements and insightful conclusions regarding the aerodynamic performance of the model under investigation.

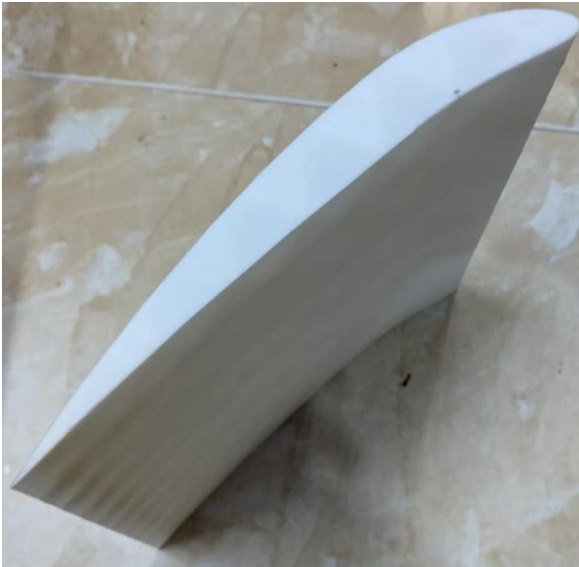


(a)



(b)

Fig:4.17 (a) & (b) : Plain Wing – NACA 8310



(a)



(b)

Fig:4.18 (a) & (b) : Wing with Denticles – NACA 8310

Following the outlined methodology, extensive experimental testing was conducted within in the wind tunnel facility, utilizing two precisely crafted 3D-printed models: one is featuring plain wing, and the other with intricately designed denticles arranged across the surface of unit Aspect ratio. The primary objective guiding this comprehensive endeavour was to thoroughly assess the reduction in skin friction drag and total drag, alongside the concurrent improvement in the lift-to-drag (L/D) ratio i.e., the aerodynamic performance.

The wind tunnel, calibrated with utmost precision, housed the securely fixed models within the test section, ensuring stability and accuracy throughout the meticulously controlled tests conducted at optimal RPM settings. Prior to experimentation, calibration of the strain gauge instrument was undertaken to guarantee precise force measurements.

Commencing with the plain wing model, comprehensive data collection was performed across a wide range of angles of attack (α) from 0 degree to both positive and negative 15 degrees, coupled with RPM settings spanning from 200 to 600 RPM. The lift, drag forces and pitching moment were calculated from the data collected by the six-component strain gauge balancing instrument.

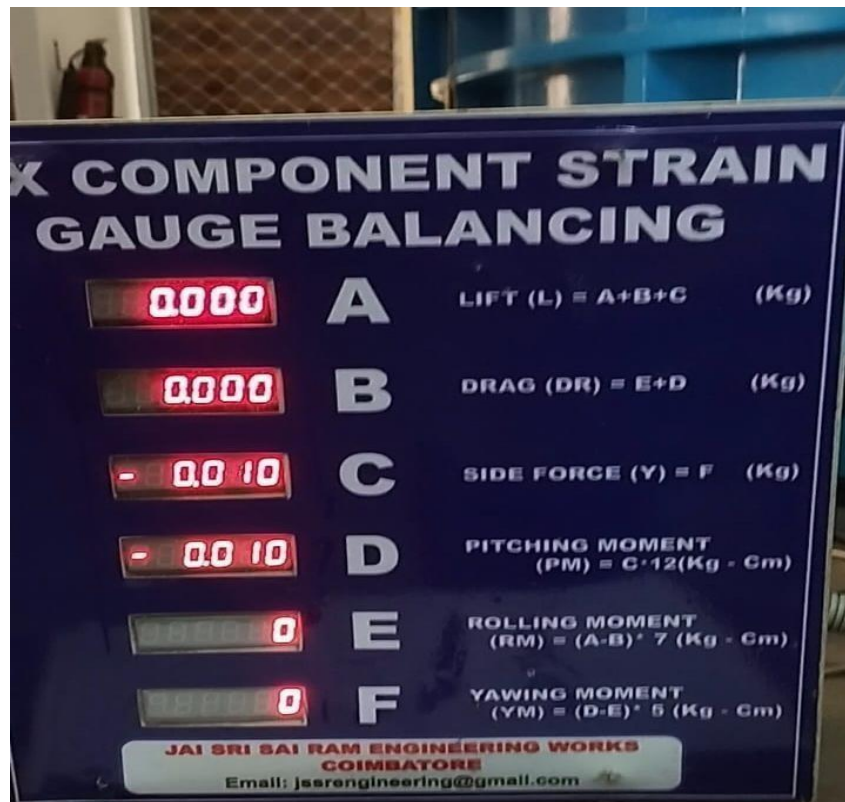


Fig:4.19 : Six Component Strain gauge balancing meter



Fig:4.20 : Testing of Plain Wing in Wind Tunnel

Following this, identical testing procedures were repeated with the wing featuring denticles. Once again, data collection ensued across the same range of angles of attack and RPM settings. The lift, drag and pitching moment were calculated from the data and the skin friction drag, total drag, and the Lift-to-Drag ratio were calculated from the data collected and compared with those of the plain wing model.



Fig:4.21 : Testing of Wing with Denticle in Wind Tunnel

In-depth analysis of the collected data unveiled a discernible reduction in both skin-friction drag and total drag achieved with the wing featuring denticles compared to the plain wing. Furthermore, calculations demonstrated significant improvement in the Lift-to-drag ratio, indicative of the enhanced aerodynamic performance conferred by the denticles.

Graphical representations were crafted to visually illustrate the findings, offering clear insights into the impact of denticle implementation on aerodynamic characteristics. In summary, the experimental testing conclusively demonstrated the effectiveness of denticles in reducing drag and enhancing the lift-to-drag ratio of the wing model, marking a significant advancement in aerodynamics.

CHAPTER – 5

RESULTS AND DISCUSSION

5.1 COMPUTATIONAL RESULTS:

The computational results for the biomimetic design of shark skin denticle were obtained through 2D and 3D geometry design approach, which involves keeping all the bodies within the boundaries test section domain of Subsonic Wind tunnel.

To carry out the simulations, the denticles were arranged in a matrix and analysed separately over a flat plate with an inlet velocity of 5 m/s to replicate the swimming condition of the sharks. The matrix which was chosen was found by designing the different types of matrices arrangements such as cross matrix, parallel matrix, and adjacent matrix. Also, the space between each denticle in the matrix was calculated and re-designed to get the optimal spacing measurements. As the selected matrix model was imported into fluent workbench, the results were obtained.

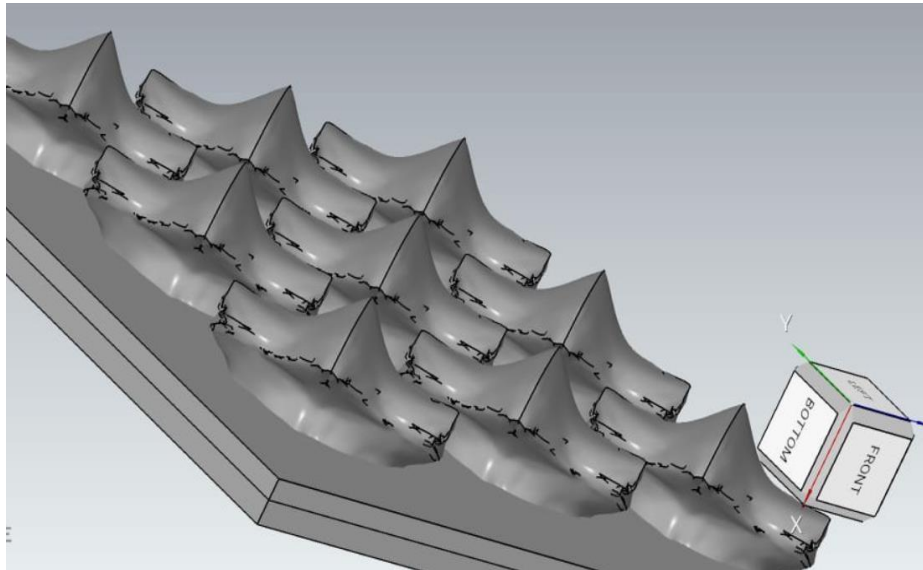


Fig:5.1 : Cross Matrix of the denticles over flat plate

Since the shark denticles has the capacity to increase the velocity of the surface where it is attached, the designed denticles are attached on a flat plate and analysed with the inlet velocity of 5 m/s to replicate the water conditions to identify the actual

increment in the velocity and the results were obtained. The results showed that the velocity increased by 2.48 m/s.



Fig:5.2 : Simulation of Denticle matrix in a flat plate

The obtained results showed a significant rise on the surface area where denticles were placed, each matrix model resulted in its own magnitude and the highest efficient matrix model pattern was selected.

As a continuation in the process of computational analysis to meet the aim of our project, the denticles have to be attached over the surface of a low aerodynamically performing wing. Hence, the Wing design process involved in selecting the airfoil shape which is poor in aerodynamic performance through airfoil tools. Three airfoils under this category were selected, and the desired performance was shown by “NACA 8310” airfoil and its L/D ratio was studied. Then the plotting co-ordinates were imported into CATIA V5 (Sketcher Workbench). These plots were then projected and the 2D design of the airfoil is obtained. This 2D design of the airfoil was imported into ANSYS 19.2 (Fluent) workbench and it was analysed to identify the reaction of the airfoil through the flow at each degree of Angle of Attack to identify the stall angle of the airfoil. As a result of the 2D analysis of the airfoil “NACA 8310” was identified that the stall angle occurred at the 12.3 degrees of Angle of Attack (α).

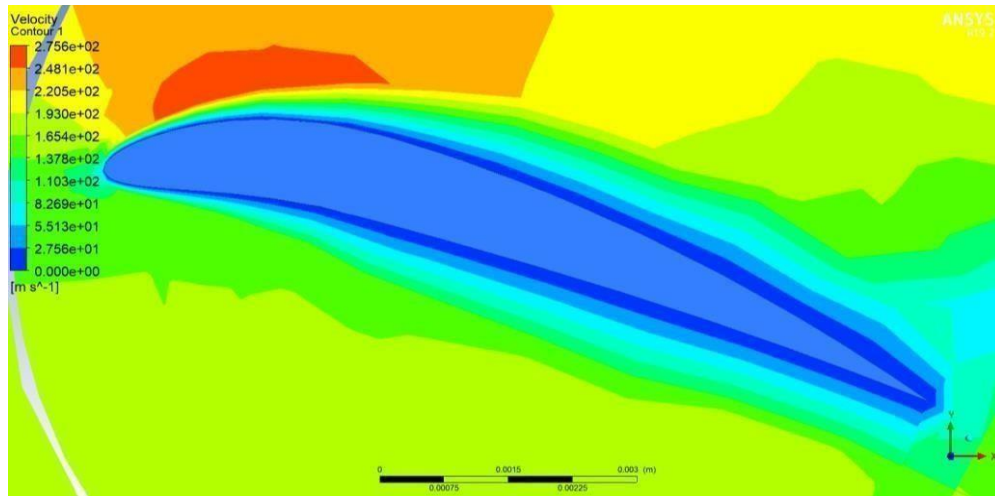


Fig:5.3 : NACA 8310 2D Analysis

As a continuation to this process, the 3D simulation was performed. Initially the airfoil is extruded as a wing (10mm x 40mm) and undergone 3D analysis simulation and the results were obtained. The results illustrates that the wing alone was prone to a quick stalling property at the angle of 12.3 degrees due to the increase in the lift induced drag

As a next step, a single denticle is placed on the centre of the wing by span, 6.5 mm of chord length from the leading edge. By simulating this design, the results showed an impactful significant improvement in the stall angle up to 25 degrees.

The denticle serves to divert the flow downward by downwash of the upstream flow, effectively ensuring its adherence to the surface. The downstream flow generated behind the denticle is entrained the upstream flow, facilitated by the intricate formation of paired Clockwise and Counter Clockwise vortices. The net vorticity produced in the leeward side is neutralized as the three vortices are overlapped and superimposed with each other. This net vorticity, increases the surface velocity downstream of the denticle. This specialized arrangement plays a crucial role in reducing the skin friction drag experienced by the wing by keeping the flow attached over the surface and thereby enhancing the overall aerodynamic efficiency.

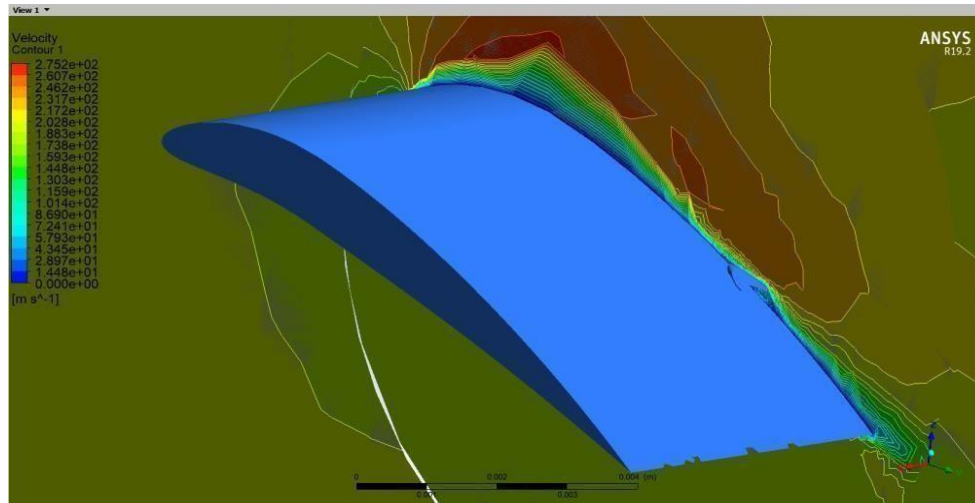


Fig:5.4 : Single Denticle on the Wing

In the same way, the denticles were arranged in a row at the same distance from the leading edge and by simulating this arrangement, the results showed the rapid improvement of the stall angle to 20 degrees. Since the number of denticles were increased, the vortex created in the space between the denticles while flowing through, the vortex is converted into a useful streamlined flow and acts as a pushing agent that increases the performance of the wing.

This vortex pairs acts as a downwash agent and produce downwash and reduces the skin friction drag which will continue across the span. The downwash elements of paired vortices looped near to the trailing edge, increases the moment at tip to tip.

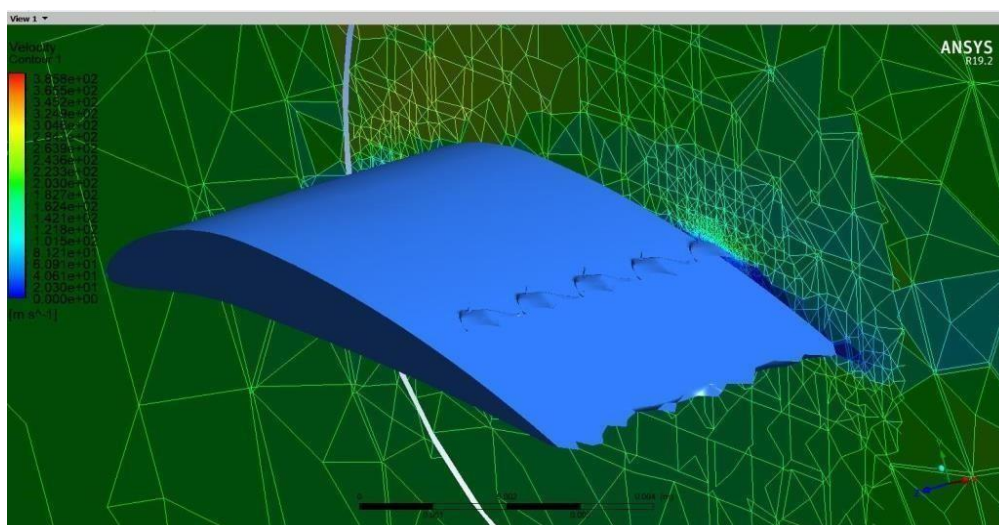


Fig:5.5 : Row of Denticles on the Wing.

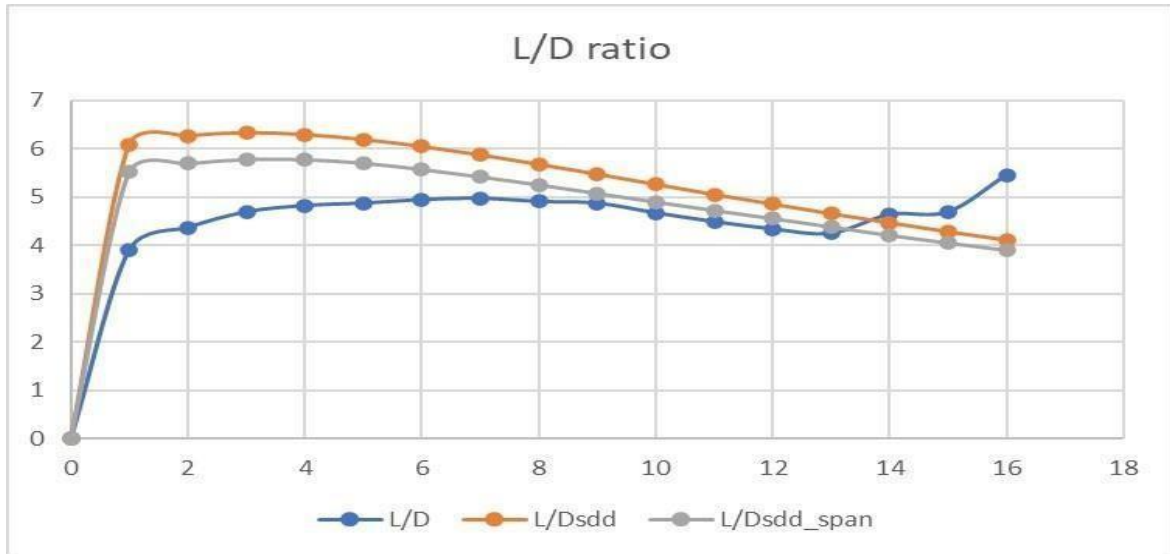


Fig:5.6 : Comparative Chart of L/D ratio

As a result of the computational Analysis, the denticles applied on the wing as a single embodiment increased the Stall Angle from 12.3 degrees to 25 degrees

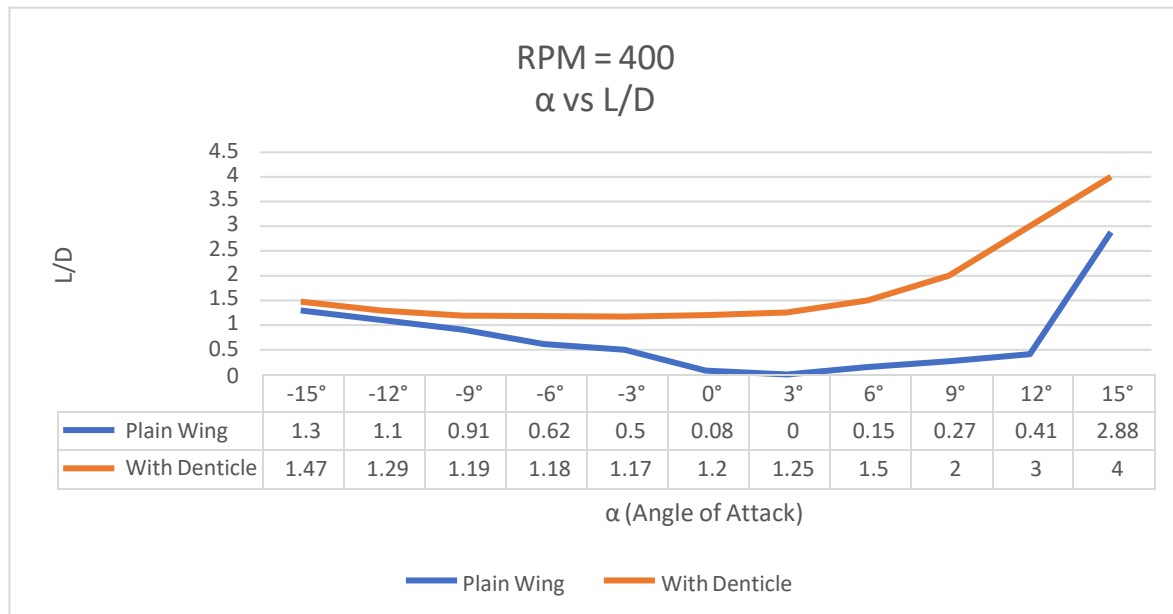
5.2 EXPERIMENTAL ANALYSIS:

In the experimental analysis, two wing models: one plain wing and one wing with denticles over the surface of airfoil series “NACA 8310” with the dimension of 200mm x 200mm was 3D printed with PLA material.

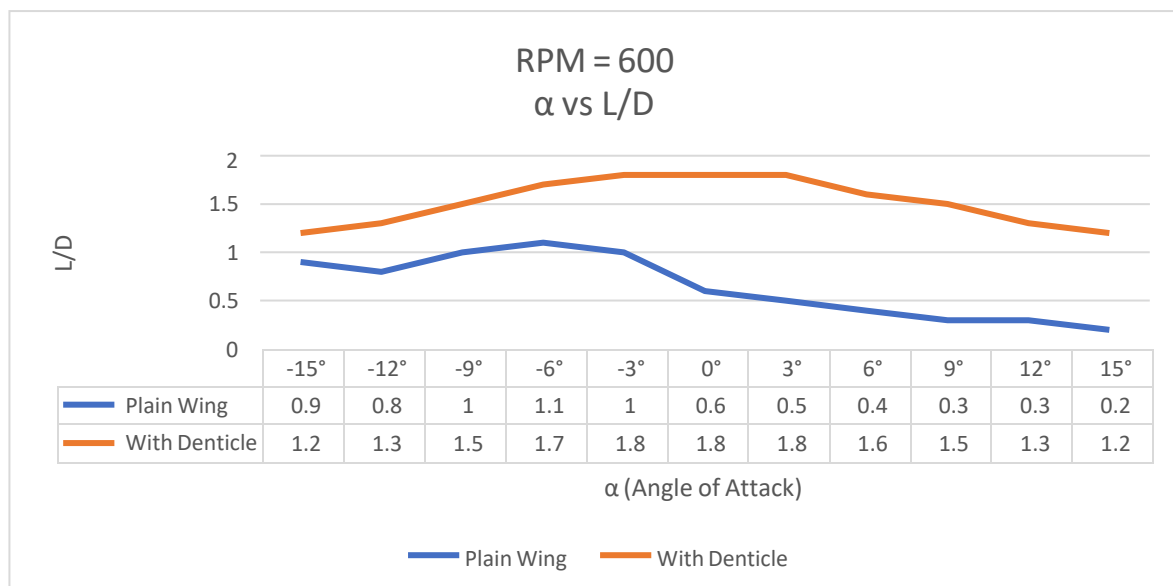
The plain wing and the wing with denticles covered all over the surface were tested in the wind tunnel for the identification of the actual aerodynamic efficiency improvisation and the reduction of skin friction and total drag of the wing with denticles in comparison with the plain wing.

The experimentation showed that the denticles covered all over the surface of the wing creates vortex pairs that produce downwash and reduces skin-friction drag which will continue across the span and chord of the wing. In the wing, the upstream flow deviates in the leading edge, develops a strong bound vortex regime, downstream of the wing produces infinite vortex loops that are spinning at tip to tip of the wing.

The infinite vortices spin together in 24 pairs developing strong bound vortex of 24 different strength. Hence, the total circulation of the bound vortex in the wing increases the lift and suppresses the skin-friction drag at half the rate of single device.



(a)

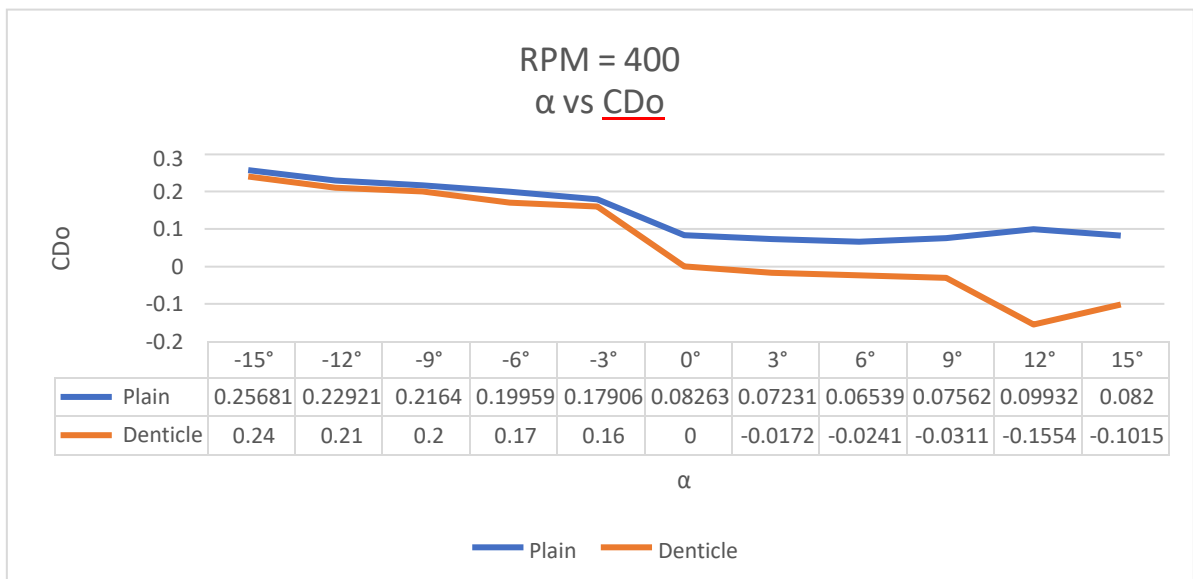


(b)

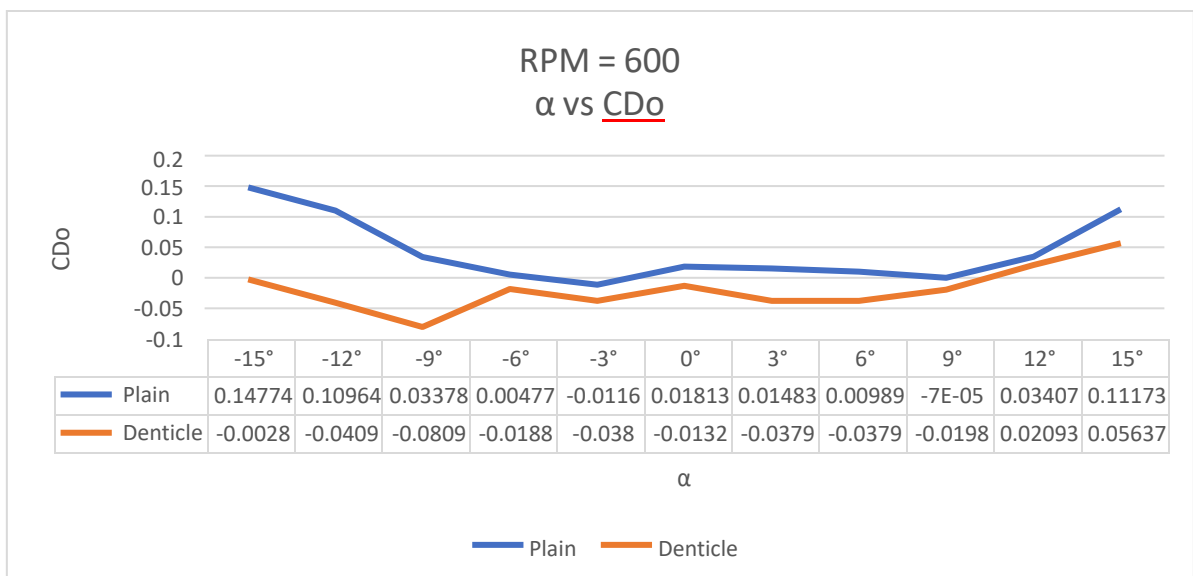
Fig:5.7 (a) & (b) : Angle of Attack (α) Vs L/D in ranging RPMs

The arrangement of the denticles over the complete wing when tested showed that the streamlines of the fluid flow increase its strength in the first row in the central spike whereas the downwash of the leeward flow meet the another denticle behind

it increases the streamline of the flow and the strength in the second denticle row increases which disrupted on the third row. The third-row streamlines follow in the same way with increased flow strength downstream to fourth row where the streamlines are rotating in between the parabolic grooves which increases the flow strength and dominates zero-surface velocity in high boundary layer flow and the transition of the fluid flow decreases as all the rotating streamlines are found somewhere on the regions to avoid the turbulence and improves the surface velocity on the surface. And hence the improvisation in the Lift-to-Drag ratio can be seen in the above graph.



(a)



(b)

Fig:5.8 (a) & (b) : Angle of Attack (α) Vs Skin Friction Drag (CDo)

The denticles attached over the complete wing results in increasing the surface velocity near to the spanwise region of the wing entirely and increases the vorticity of the wing in overall at extreme stall region. Thus, 405% the skin friction drag is reduced in the entire wing that results in increase in lift of the unit aspect ratio of the poor aerodynamic efficient wing. The stall region is also exceeded where the flow separation begins only at 20 degrees.

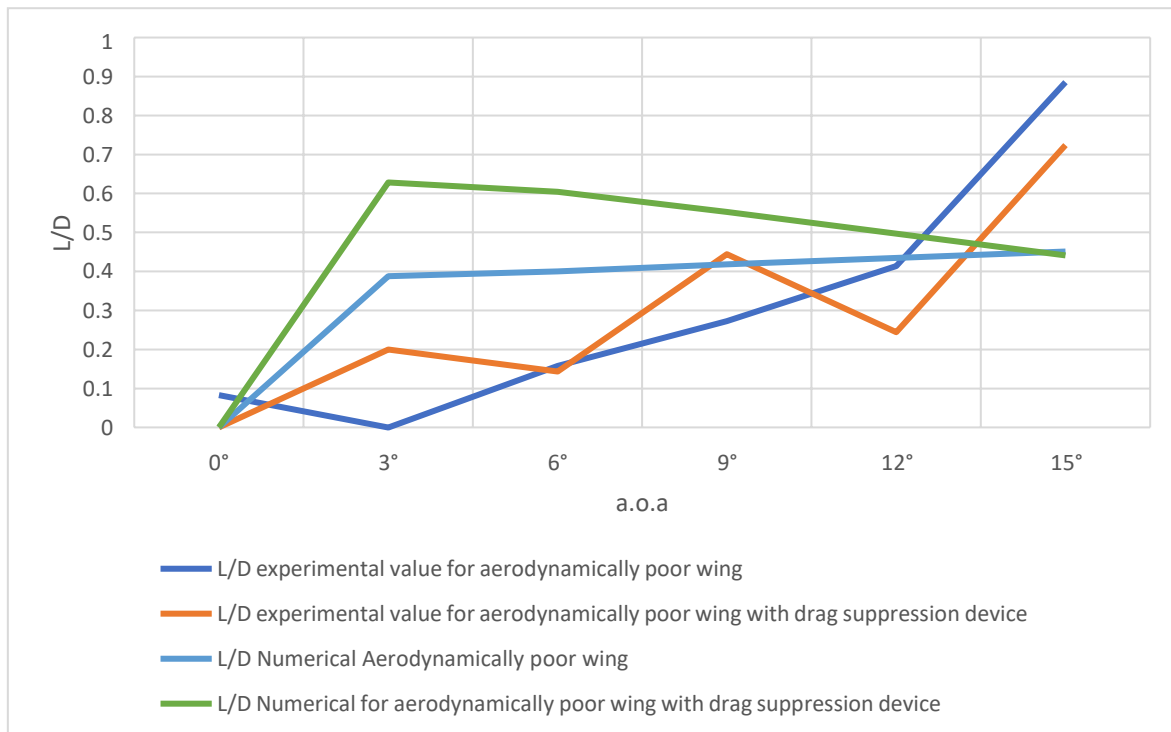


Fig:5.9 : Comparison chart of Experimental and Numerical Simulation data.

The numerical simulation aerodynamic efficiency data interprets the aerodynamically poor efficient wing with denticles improves the efficiency by suppressing the skin friction drag by 200% and total drag by 105%. Whereas the experimental test of aerodynamic efficiency data interprets the aerodynamically poor efficient wing with the embodiment under different Reynolds number improves the efficiency by suppressing the skin friction drag from 405% and the total drag by 250% at stall angle of attack.

The embodiment takes the shape of biomimicry of shark denticle and few geometrical structure variations are adopted for procuring a good amount of drag suppression. The fluid streamlines take the form of stagnation point in the droop nose and continue over the frontal two edges of cross vault hyperbolic paraboloid

with decrease in velocity and drifted downwards towards the grooved parabolic arches with increase in velocity that continues unto the port and larboard side of the outlying spikes. The flow streamlines from the nose droop to the central spike increases its velocity and push the streamlines downward towards the downstream which increases the vorticity of the flow. The vorticity of the flow is improvised in central spike with high strength and the larboard outlying spike with low strength. The net resultant vorticity experienced downstream of the denticle to create downwash were the stream velocity near to the surface increases which in turn the flow acceleration starts behind the denticle structure. Thus, the wetted area was reduced to yield the minimum skin friction coefficient across any planar region.

The boundary layer thickness near to the surface increases as the denticle is kept in any fluid dynamic bodies that possess low Reynolds number flow. The momentum boundary layer thickness is said to increase the fluid streamlines velocity near to the surface of any fluid dynamic bodies subtend to carry a rotating vortex in between the matrix array gaps. The energy boundary layer thickness increases with rotating vortices in the matrix array gaps where the fluid subtends to increases its surface velocity. Henceforth, the skin friction drag reduced 400 times the actual fluid dynamic skin friction drags. Also, the total drag reduced 250 times the actual fluid dynamic total drags.

CHAPTER – 6

SUMMARY AND CONCLUSION

6.1 SUMMARY:

This project is aimed to investigate the science behind the fastest hydro predators' "Sharks" for the phenomenal speed and efficiency. This Study proves that the reason behind is the passive geometric, dynamic structure "dermal denticles" that spreads across the body of the shark. This result is obtained by studying, designing, analysing and iterating. Additionally, introducing a biomimetic design of shark denticle in aviation industry generally helps us in the improvisation of the overall performance of the aircraft at subsonic and transonic levels and the position of the application of the denticle plays a crucial role in controlling the vortex flows thus in turn results in smoother and more stable laminar airflow, reducing energy consumption and enhancing the manoeuvrability of the aircraft.

6.2 CONCLUSION:

The designed shark denticle device is suitable for all incompressible flow fluid dynamic applications. The denticle may be a single or group of identical shapes perform the increase in near surface velocity in any attachment region of any fluid dynamic bodies at low Reynolds number flows. The designed denticle deals with drag suppression that decreases the skin friction drag ultimately in all regions of low Reynolds number flows. The embodiment of shark denticle shaped biomimicry creature takes the shape of shark skin in micro structure of fitness ratio 1.

In conclusion, the biomimetic application of shark denticles offers a compelling avenue for enhancing the aerodynamic performance of aircraft wings. Computational results indicate that the approach has the potential to reduce drag, improve fuel efficiency, and create more sustainable aviation solutions. As research and development in this area is under progress, the successful translation of these findings into practical, real-world applications could usher in a new era of more efficient and environmentally friendly aviation technologies. However, further experimentation is required to validate these computational results and address the technical challenges associated with the implementation of this biomimetic design.

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DRAG SUPPRESSING DEVICE USING BIOMIMETIC DESIGN

FIELD OF INVENTION
MECHANICAL ENGINEERING

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