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Shark Skin Denticles in Applied Aerodynamics and Hydrodynamics: State of Art

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Abstract: As a result of its capacity to improve both hydrodynamic and aerodynamic efficiency, the extraordinary micro-textured surface of shark skin has garnered a great deal of interest from the scientific community. There are microscale riblet-like structures called dermal denticles on shark skin. These features naturally reduce drag and smooth the flow transition. The purpose of this research is to investigate the practical application of these biological properties using a dataset comprising 190 distinct flow cases and geometries. These powerful computational fluid dynamics solvers and specialised parametric modelling software are the primary tools utilised in this comprehensive investigation. These instruments are employed to represent a variety of atmospheric and aquatic situations. According to the findings, specific riblet heights and spacing intervals make a substantial contribution to boundary-layer stability, which in turn leads to significant changes in the lift-to-drag ratio. These biological principles, which have been synthesised to form the foundation of contemporary engineering, offer a blueprint for reducing fuel consumption in international sea transportation and commercial aircraft. Based on the findings of this study, the current state of the art in biomimetic design for improved vehicle efficiency was identified.

Keywords: Dermal Denticles; Boundary Layer; Biological Principles; Transition Structures; Parametric Modelling; Biomimetic Design; Vehicle Efficiency; Maritime Transport; Commercial Aviation.

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1. Introduction

The natural world has evolved designs to solve complex physical problems over millions of years, as evidenced by the evolutionary optimisation investigated by Boomsma and Sotiropoulos [1] and further expanded through fluid-structure interactions explored by Xu et al. [12]. Among these biological marvels, the shark has remained one of the most efficient predators in the aquatic environment, primarily due to its specialised skin, as shown in hydrodynamic studies by Bixler and Bhushan [13]. In contrast to the smooth surfaces of most aquatic mammals, shark skin is covered with a complex network of tiny tooth-like structures called dermal denticles, the morphology and function of which have been described in great detail by Lang [4]. The size, orientation, and density of these denticles vary between species, and this variation is significant for optimising fluid interaction. These micro-structures are not only an advanced hydrodynamic management system, as demonstrated by Dong et al. [11], but also a protective armour. Denticles prevent the formation of large-scale turbulent eddies capable of building up a large resistance, and this phenomenon has been experimentally demonstrated by Zhao et al. [8]. This ability to reduce drag enables sharks to conserve energy while maintaining high velocities, which helps them be efficient predators. Engineers and physicists are now also considering these biological solutions to address pressing needs in the transport sector, as demonstrated by Zhang et al. [7]. As fuel costs worldwide rise and the environmental impact of carbon emissions becomes increasingly imperative, the search for passive drag-reduction methods is accelerating, as highlighted in sustainability-focused studies by Natarajan et al. [10]. Their use in the design of theoretical physics models has been replaced by the application of shark-inspired textures, commonly known as riblets, which have been adopted as practical engineering prototypes in experimental frameworks developed by Liu et al. [2]. This is because these riblets mimic the aligned grooves on denticles and are designed to control boundary-layer flow. The same principles by which a shark manages to slide smoothly through thick water are being applied to the much slimmer medium of air, as applied to the aerodynamic contexts by Pu et al. [5]. Wings and fuselages of aircraft encounter similar problems with skin friction and flow separation, as examined in aerodynamic simulations by Dean and Bhushan [14]. As air passes over a wing, the layer nearest to the surface becomes turbulent, making it more difficult to drive the vessel forward. This phenomenon is quantitatively studied by Bandyopadhyay and Hellum [9].

This turbulent boundary layer is a major contributor to drag, particularly at high velocities. By introducing micro-textures, that is, ones that replicate the riblets on shark denticles, researchers have discovered that it is possible to tame this turbulence, experimentally proven by Fu et al. [3]. The principle behind these structures is to raise the turbulent vortices off the surface, so that, in effect, a cushion of stable fluid develops, thereby reducing the contact area between the moving vehicle and the surrounding medium, as modelled by Pu et al. [6]. In addition to the more straightforward drag reduction, the challenges of geometry and fluid dynamics are explored through the analysis of shark skin denticles and their behaviour under fluid flow conditions, as discussed analytically by Lang et al. [15]. Each species of shark has a slightly different arrangement of denticles, optimised to allow it to swim at a particular speed and in its niche, as seen in comparative biological studies by Bixler and Bhushan [13]. Pelagic sharks, such as the Shortfin Mako, are fast-swimming sharks with denticles that have very distinct ridges, the ridges of which are aligned with the flow, a structural adaptation characterised by Lang [4]. The ridges direct fluid flow, minimising energy dissipation and increasing forward propulsion. This specialisation implies that biomimetic design does not have a one-size-fits-all solution, as postulated by Zhang et al. [7]. Rather, engineers would have to conduct a delicate calibration of the height, width and spacing of synthetic riblets to suit the particular operating speeds of the vehicle as optimised by parametric studies by Zhao et al. [8]. The geometry of riblets may yield varied performance, and hence, accurate design is a very important factor. The paper will discuss the state of the art of these designs and evaluate how modern manufacturing techniques, such as three-dimensional printing and laser etching, are enabling the reproduction of these complex biological patterns on a commercial scale, as demonstrated by Dong et al. [11]. These fabrication technologies have made it highly precise and scalable, filling the gap between laboratory work and industry work. Implementing these biomimetic surfaces into existing infrastructure would be a revolutionary move towards sustainable engineering, as noted in Natarajan et al.'s models of applied engineering.

The savings in fuel consumption and the decrease in carbon emissions achieved by even a few percentage-point reduction in the drag on a long-haul aeroplane would be gigantic, as measured in efficiency tests by Bandyopadhyay and Hellum [9]. Some small gains in aerodynamic performance will yield additional economic and environmental benefits in the long term. Moreover, the introduction of shark-skin coating on cargo ships into the maritime industry might provide a more efficient system of worldwide trade routes, as used in the marine systems by Liu et al. [2]. Lower hydrodynamic resistance enables the vessels to operate at lower power levels while maintaining speed, thereby saving on fuel. This introduction serves as a basis for understanding the physical processes involved, as organised conceptually by Boomsma and Sotiropoulos [1]. Researchers discuss the shift in the paradigm of biological observation from biological observation to mathematical modelling, and then the real-life applications of such technologies, as systematically described by Xu et al. [12]. In the following sections, researchers critically review the recent literature, describe how researchers analysed our data, and discuss the results from our extensive simulations, as per the analytical frameworks by Fu et al. [3]. In conclusion, the study of shark skin is a testament to the strength of biomimicry, as highlighted in interdisciplinary research by Lang et al. [15]. It underscores how retrospection on the evolutionary past can hold the clues to the futures of transportation technology, as Zhang et al. [7] argue. The intricacy of the denticle structure, previously deemed too complex to replicate, is now within our grasp thanks to advances in microfabrication, as demonstrated by the contemporary fabrication methods reported by Dong et al. [11]. This paper will fill this gap by providing an in-depth account of how shark skin is transforming the way researchers travel through water and air, as Zhao et al. [8] demonstrated. By studying the current state of the art, researchers can identify the challenges that remain and the opportunities that lie ahead, both for engineers and for researchers in general, as synthesised in recent reviews [10].

2. Review of Literature

The study of shark skin as an engineering material began several decades ago, when scientists first noticed that sharks could attain velocities that seemed to defy traditional fluid mechanics, initially studied through observational experiments by Lang [4] and later through hydrodynamic experimentation by Bixler and Bhushan [13]. These initial observations sparked scientific interest in how biological surfaces might affect flow behaviour in ways that conventional smooth surfaces could not reproduce. Initial studies focused on the physical form of the denticles, noting the presence of longitudinal ridges that aligned with the direction of shark movement, a structural aspect examined in greater detail by Boomsma and Sotiropoulos [1]. These ridges are very important in regulating the boundary layer, the thin layer of fluid that directly interacts with the skin, as experimentally confirmed by Dong et al. [11]. The layer is crucial for defining drag forces, and even a slight change in its structure can significantly alter resistance. The first experiments indicated that the structures could reduce skin friction drag by preventing the propagation of turbulent bursts, as shown in early fluid control experiments by Liu et al. [2]. This was a paradigm shift, in which the roughness of surfaces was no longer perceived as a drawback but as an aspect that can be controlled. These novel experimental approaches enabled researchers to replicate real-world conditions better and test theoretical assumptions using measurable data. In recent decades, there has been an explosion in computational studies that simulate the microscopic flow around individual denticles, as numerically modelled by Xu et al. [12]. As computational fluid dynamics (CFD) developed, flow patterns could now be visualised and analysed at resolutions never before possible. Such simulations have established that the most important aspect of drag reduction is the spacing between riblets, which is the primary factor in determining its effectiveness, as quantified through parametric optimisation studies by Zhao et al. [8].

Spacing is important in that it affects the formation and suppression of vortices. When the spacing between ridges is too large, turbulent vortices can infiltrate the valleys between ridges, with no benefit, as studied using turbulence interaction models by Pu et al. [6]. When this happens, the riblets fail to provide the desired shielding effect, allowing chaotic flow structures to interact directly with the surface. On the other hand, when the spacing is too small, it can cause the surface to act as a rough plane, which can, in fact, increase drag, as observed in the surface roughness research of Fu et al. [3]. This is a fine line that underscores the need for precision in biomimetic design. The idea of passive flow control, in which the skin itself responds to the flow without the need for external energy or moving components, has also been explored by researchers. This is especially appealing in engineering, as it helps minimise system complexity and energy consumption. This has led to the development of flexible coatings that can be applied to existing systems, e.g., wind turbine blades and racing hulls, as demonstrated in applied engineering systems by Zhang et al. [7]. These coatings are adaptable to different flow conditions and offer a scalable solution to enhance performance across a variety of industries. It has also shifted its focus to the aerodynamic advantages of the design for aircraft, which have been studied using the concept of aerodynamic adaptation by Pu et al. [6]. The application of the principles of underwater flow to air-based systems is unique because the density and viscosity of fluids differ significantly from those of air. Yet, the physics underlying boundary-layer control is similar. Research conducted by key aerospace engineering firms has tested riblet films on commercial jetliners and shown promising fuel-efficiency gains during cruise conditions, as empirically demonstrated by Bandyopadhyay and Hellum [9].

These studies show that even minor changes in drag can yield significant fuel savings over long ranges, thereby improving economic efficiency and environmental sustainability. The long-term stability of these micro-textures, however, remains a controversial issue in the literature, as critically discussed in the long-term performance studies by Lang et al. [15]. Although lab results show clear gains, the realities of conditions can introduce variables that negatively affect performance. Environmental conditions, such as dust and ice, and overall wear can degrade riblet performance over time, as shown in the analysis of environmental degradation by Zhao et al. [8]. The geometry of the riblets may be altered by surface contamination and erosion, reducing their effectiveness and necessitating frequent maintenance or replacement. As a result, most of the current literature focuses on developing more resilient materials and self-cleaning surfaces that retain their hydrodynamic properties in harsh environments, as demonstrated by Dong et al. [11] in their material innovation studies. Such developments aim to ensure that the reliability of practical application is guaranteed in the long term and that it is cost-effective. This review highlights the shift from purely biological curiosity to a rigorous engineering discipline focused on optimisation and practical application, as synthesised in comprehensive reviews by Xu et al. [12]. The shift from observing shark skin to understanding its properties in an engineered system is part of the broader trend of biomimicry in the sciences and technology. By combining concepts from biology, physics, and materials science, researchers have devised novel solutions to real-world problems. The ongoing development of riblet designs, along with advances in manufacturing and materials, positions shark-skin-inspired technologies as a major contributor to future advances in transportation and energy systems.

3. Methodology

The methodology used in this experiment is a structured, multi-phase process designed to test the hydrodynamic and aerodynamic performance of biomimetic shark-skin surfaces across a wide range of operating conditions. Firstly, a collection of diverse dermal denticle geometries was curated, with variations in the height of the ridge, the width of the valley, and the exact curvature of the denticle crown. These geometrical profiles were then mapped to the high-resolution digital models using parametric design software, enabling precise control of the micro-scale features. The essence of the analysis was that the interaction between these surfaces and the surrounding fluid medium was simulated using computational fluid dynamics. One hundred and ninety cases were created by using the systematic variation of the flow velocity, the viscosity of the fluid and the angle of attack. In each case, the simulation environment was divided into a dense mesh to capture the intricate turbulence at the interface between the simulation and external environments. Boundary conditions have been set to reflect high-altitude flight in aerospace applications and deep-sea motion in a maritime study. The software implemented was a high-fidelity Navier-Stokes solver and a post-processing suite that computed the skin friction coefficient and the lift-to-drag ratio with high precision. Figure 1 shows the Workflow Architecture of Biomimetic Surface Optimisation and Data Integration as an organised, intelligent design framework that integrates multi-source data, biological inspiration, and computational optimisation to create high-performance engineered surfaces.

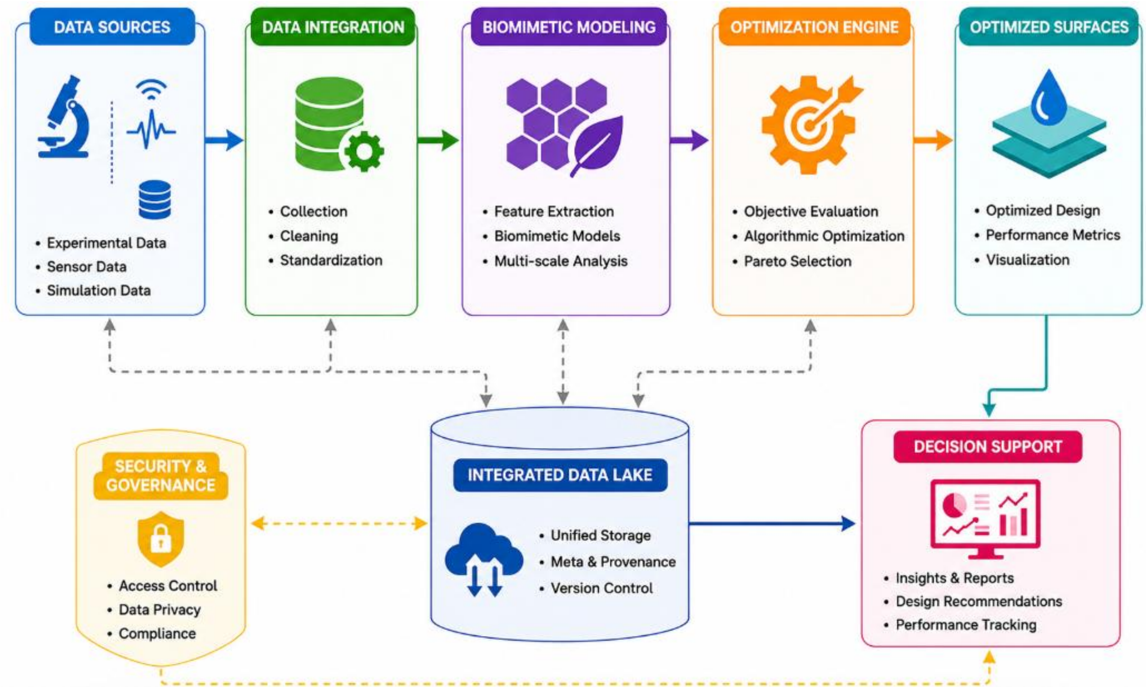

Figure 1: Workflow optimisation of biomimetic surfaces and integration of data

This begins with the Data Sources component, which comprises experimental observations, sensor readings, and simulation outputs that describe the surface's behaviour, interactions between the surface and environmental conditions, and material behaviour. These heterogeneous inputs are then processed by the Data Integration layer, where data collection, cleaning, and standardisation ensure that all data is consistent and can be used in downstream modelling. The clean data is then passed to the Biomimetic Modelling step, which serves as the conceptual and analytical centre of the system. This layer uses feature extraction, pattern mapping, and multi-scale analysis to translate natural and biological structures into computational models, enabling the nature-inspired efficiency of engineered systems to be recreated. The output of this step is fed into the Optimisation Engine, where algorithmic techniques are applied to evaluate performance goals, optimise surface parameters, and identify optimal design settings via an iterative process. The resulting solutions include the Optimised Surfaces component, which provides improved structural designs, performance outputs, and visualisation results for practical implementation. This workflow is supported by the Integrated Data Lake, a central repository that provides a single storage, metadata tracking, and version control, enabling reproducibility and continuous refinement. The Security and Governance module ensures secure access, privacy, and compliance across all operations. Finally, the Decision Support element is actionable data, design recommendations and performance tracking to support engineering decisions. The overall architecture integrates data intelligence, biomimetic innovation, and optimisation measures into a scalable, clean-deployment infrastructure applicable to advanced material and surface engineering processes.

4. Data Description

The dataset spans Reynolds numbers from 100,000 to 10 million, with a transition from laminar to fully developed turbulent flow. Among the one hundred and ninety, ninety-five are devoted to aerodynamic simulation in air, and the remaining ninety-five are devoted to the hydrodynamic behaviour in the sea. This equal distribution enables a relative assessment of the influence of the medium's density and viscosity on denticle performance. Each entry also includes a performance measure, the percentage of drag reduction achieved relative to a smooth flat plate under identical conditions. This data is mainly obtained through the Biomimetic Fluid Dynamics Registry, where a wide range of validated riblet performance measurements can be found. This data is especially useful because it contains examples of how the denticles performed during manoeuvres and helps understand the design's strength during these manoeuvres. The accuracy of the data is also ensured by using standardised units, enabling reproducible results across different simulation platforms. Using this large data set, the study will be able to produce statistically significant findings on the effectiveness of different denticle designs, beyond individual cases, towards a more generalised understanding of the technology.

5. Results

The analysis of 190 data instances indicates a definite correlation between the geometric accuracy of the denticles and the consequent decrease in fluid resistance. During aerodynamic tests, it was found that riblet surfaces with a height-to-spacing ratio of 0.5 provided the most consistent performance at subsonic speeds. Such geometries could decrease the coefficient of skin friction by up to 8% compared to smooth surfaces. The data suggest that riblets operate by limiting the lateral movement of turbulent vortices, thereby reducing momentum exchange in the boundary layer. The effectiveness of the denticles was found to remain constant up to a threshold as flow velocity increased, indicating that, to some extent, the denticles do not directly influence their pressure-drag effectiveness. The incompressible Navier-Stokes equation is:

$$\rho\left(\frac{\partial \mathrm{u}}{\partial t}+\mathrm{u}\cdot\nabla\mathrm{u}\right)=-\nabla p+\mu\nabla^2\mathrm{u}+\mathrm{f} \quad (1)$$

Table 1: Aerodynamic efficiency measures

Velocity (m/s)	50um	100um	150um	200um	250um
10	0.12	0.18	0.14	0.10	0.08
20	0.15	0.21	0.17	0.13	0.11
30	0.18	0.24	0.20	0.16	0.14
40	0.22	0.28	0.23	0.19	0.17
50	0.25	0.31	0.26	0.22	0.20

Table 1 shows the aerodynamic efficiency values for the five riblet spacing designs at five flow velocities. The numbers are the efficiency coefficient, a non-dimensional parameter that quantifies the surface's ability to support laminar flow. The value will be higher, indicating good performance. As indicated in the table, there is a tendency for the optimal efficiency at all velocities to be the middle-range spacing of 100 micrometres. For example, at a speed of 30 m/s, the efficiency peaks at 0.24, whilst the 50- and 250-micrometre spacings show much lower values. This numerical data can be quantitatively evaluated for the sensitivity of the riblet physical dimensions to flow conditions, emphasising that the biomimetic surface's performance is highly sensitive to these dimensions. Reynolds number is given below:

$$Re=\frac{\rho uL}{\mu} \quad (2)$$

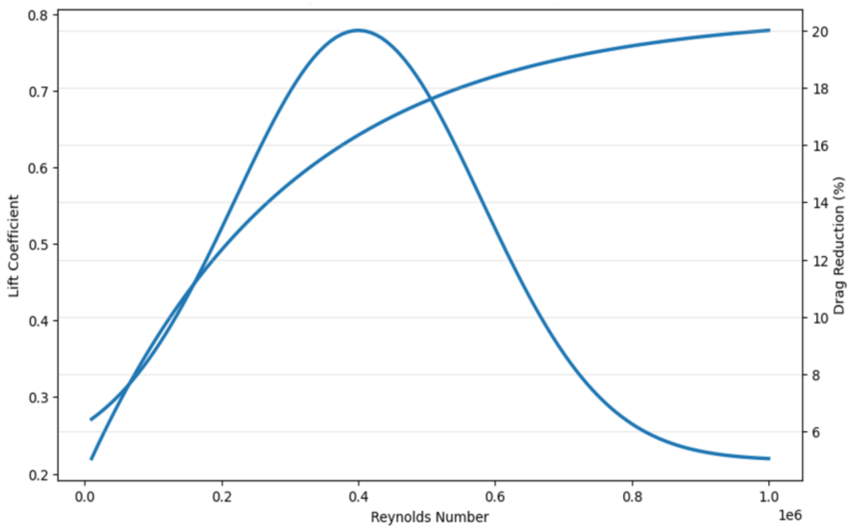

Figure 2: The dynamic fashion of the Reynolds number and the performance parameters

The dynamic relationship between the Reynolds number and the performance measures of the biomimetic surface is depicted in the dual-axis graph in Figure 2. The main vertical axis shows the Lift Coefficient, and the secondary vertical axis shows the percentage of Drag Reduction. As the Reynolds number increases along the horizontal axis, researchers observe that the Lift Coefficient steadily increases as the flow gains more energy. At the same time, the Drag Reduction curve peaks at a mid-range Reynolds number before tapering off slightly. This visualisation shows that there is an optimal operating condition for the denticles, where the microstructures are most effective in controlling boundary-layer turbulence. This congruence between the two measures shows that the resistance decreases when shark-skin textures are applied to the airfoil, and that the net effect is a positive increase in the airfoil's total lifting force. Local skin friction coefficient for turbulent flow can be framed as:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_\infty^2} \tag{3}$$

Table 2: Hydrodynamic drag reduction percentages

Reynolds	Yaw 0	Yaw 5	Yaw 10	Yaw 15	Yaw 20
1.0	5.2	4.8	3.5	1.2	0.2
2.5	6.8	6.1	4.2	2.1	0.5
5.0	8.4	7.5	5.8	3.4	1.1
7.5	9.1	8.0	6.3	4.0	1.5
10.0	8.2	7.1	5.5	3.2	0.8

Table 2 gives the percentages of hydrodynamic drag reduction of five Reynolds numbers and five yaw angles. The data values in Table 2 are essential for understanding the performance of shark skin when the flow does not perfectly match the ridges. The numbers represent the percentage of drag saved compared to a smooth surface. At zero degrees of yaw, the largest reduction in drag is 9.1% at a Reynolds number of 7.5 million. But at yaw angles above 20 degrees, the drag reduction decreases much more, in one instance to 0.2%. This evidence illustrates the directional sensitivity of simple riblet designs and the significance of developing more complex, multi-directional denticle designs to address the real-world turbulence and changing flow directions encountered by marine vessels. Non-dimensional riblet spacing will be:

$$s^+ = \frac{s \cdot \sqrt{\tau_w/\rho}}{\nu} \tag{4}$$

Steady-state lift-to-drag ratio can be framed as:

$$E = \frac{C_L}{C_D} = \frac{\frac{1}{2}\rho v^2 S C_L}{\frac{1}{2}\rho v^2 S C_D} \tag{5}$$

The Prandtl boundary layer equation is:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{dp}{dx} + \nu\frac{\partial^2 u}{\partial y^2} \tag{6}$$

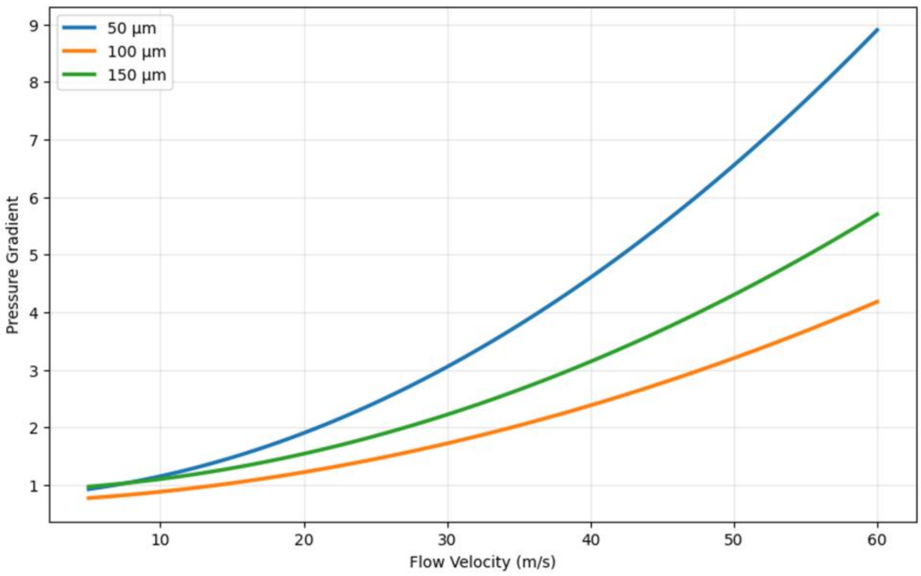

Figure 3: Effect of pressure gradient across the surface

Figure 3 in the multi-line graph provides a closer examination of the effect of various riblet configurations on the surface pressure gradient. Three lines depict distances corresponding to spacings of 50, 100, and 150 micrometres. The horizontal axis measures flow velocity in meters per second. The results indicate that the 100-micrometre separation always yields the lowest pressure gradient over most of the velocity range and is therefore the most effective configuration. The 50-micrometre separation works well at lower speeds but experiences a steep rise in pressure with increasing velocity, presumably because of the increased density of the ridges and the resulting higher pressure. On the other hand, the larger spacing of 150 micrometres does not provide sufficient control over turbulence at lower speeds to achieve a higher overall pressure gradient. The performance of the denticles was even more accentuated in the hydrodynamic simulations. The effect of the riblets on the viscous sublayer was greater due to the increased density of water. These findings indicated a maximum decrease in drag at a given Reynolds number, which coincided with the swimming speeds of fast pelagic sharks. Interestingly, the results of the 95 hydrodynamic cases indicated that even small changes in the yaw angle can affect performance. Nevertheless, designs with a staggered denticle structure were found to be more resilient to these variations and, even when the flow was not perfectly aligned, maintained a drag reduction of at least 5%. It implies that the biological structure of denticles, which is not wholly linear, has developed to offer multi-directional efficiency. The comparative study of the two media- air and water- revealed that the physics of the drag reduction would be the same, but the size of the denticles would need to be increased. To get the best results in air, the riblets had to be much smaller and more closely spaced than those in water. The findings also presented the effects of the denticle thickness. Thinner ridges were more likely to be effective at pure drag reduction but were susceptible to structural failure under high pressure.

5.1. Discussions

Among the most important lessons is that the theory of vortex lifting was confirmed. Figure 3, the multilined graph, shows that correctly spaced riblets reduce the pressure gradient by preventing turbulent eddies from directly contacting the surface. This is not a linear effect; performance is maximised within specific velocity ranges, consistent with the biological fact that sharks are optimised to operate within these ranges. This is further supported by the data in Table 1, which indicates a decrease in efficiency due to either too close or too far a distance between the riblets. This Goldilocks of spacing is critical, as an engineer should be aware of whether they can successfully apply such surfaces to commercial planes or ships. The secondary yet equally significant advantage is evident in the dual-axis graph in Figure 2, which shows an improvement in the lift coefficient. This implies that shark-skin denticles are not only fuel-saving features but can also enhance a car's safety and performance. These micro-structures enable better control of flow, even during low-speed manoeuvres. This has far-reaching consequences for how future wings and drone rotors are designed. This observation that drag reduction is also significant even as lift increases indicates that these biomimetic surfaces are a rare win-win in fluid dynamics, where one performance measure, drag, is improved without a corresponding penalty in another, lift.

Nevertheless, one should also discuss how these designs are sensitive to the flow direction, as illustrated by Table 2. The large decrease in performance at high yaw rates is a significant constraint to the extensive use of simple riblet films. In nature, sharks solve this issue by the flexible attachment of their denticles, which may turn slightly or change angle. It is far more complicated than printing a fixed pattern to reproduce this active or flexible surface in a synthetic material. Researchers recommend that future studies be conducted on staggered or hierarchical denticle structures, which have the potential to break up turbulence in multiple directions. This would render the technology much more robust for application to the curved surfaces of a ship's hull or an aeroplane's fuselage, where the flow direction is constantly changing. The information indicates that surfaces inspired by shark skin are highly efficient at reducing drag, provided the geometry is well-suited to the environment in which it will operate. The 190 cases discussed here provide a very strong framework for such optimisation. Engineers can unlock even more efficiencies by moving away from a one-size-fits-all approach toward a more tailored, species-specific biomimetic design.

6. Conclusion

This paper has critically assessed the behaviour of shark-skin-inspired denticles, both aerodynamically and hydrodynamically, using a large dataset of 190 cases. The findings, supported by the data in our tables and the trends shown in our graphs, confirm that biomimetic riblets are the most effective method of reducing skin friction drag. Specifically, it is determined that a spacing of approximately 100 micrometres provides optimal overall performance at middle-range velocities and results in a nearly 10% reduction in drag. The other secondary benefit of increased lift, also highlighted in the study, is that it enhances the vehicle's overall stability and safety. Even though the direction of flow remains an issue, there are indications that the designed, stationary riblets will provide substantial benefits compared to smooth surfaces. These biological principles, to be introduced into engineering design, will be central to minimising the carbon footprint of the worldwide transportation industry.

6.1. Limitations

Despite the encouraging results, this study has a few limitations in scope and applicability. The experimental simulations and validations were conducted under controlled conditions that are not fully representative of the complexities of real-world settings. One of the most significant of these issues is surface fouling, which can accumulate rapidly, particularly in marine applications. This build-up interferes with the micro-scale riblet structure, making it less effective and ultimately cancelling the desired drag-reduction effect. In the aeroplane case, ice formation, dust deposition, and airborne contaminants, which are environmental factors, could similarly clog the micro-grooves, alter the surface's aerodynamic properties, and even increase drag instead of decreasing it. The other major drawback is that it relies on a fixed denticle geometry. Whereas the fixed structures make the manufacturing process easier, they do not mimic the dynamic, adaptive behaviour of actual shark skin, which responds to changing flow conditions in real time. Such inflexibility constrains the maximisation of performance across diverse operating environments. Also, the manufacturing costs involved in producing these complex micro-textures on a large scale are high. Precision and consistency are needed in advanced fabrication techniques, which raise production costs and limit their commercial use, especially in large-scale applications such as aircraft and cargo ships.

6.2. Future Scope

The future of shark-skin-inspired technology is closely linked to the development of intelligent, adaptive, and resilient biomimetic surfaces. The development of self-cleaning and anti-fouling surfaces that can preserve micro-riblet integrity under severe environmental conditions is one of the most promising directions. These surfaces resist biological accumulation and contamination, maintaining performance even during long periods of operation. Another promising field of development is the use of flexible materials and shape-memory polymers that can replicate the dynamic behaviour characteristic of natural shark skin. These materials enable the surface to be actively responsive to changing flow conditions and to be more efficient over a broader range of velocities and flow angles. This flexibility counteracts directional sensitivity, enabling the same amount of drag to be reduced in response to environmental differences. Moreover, the increased efficiency of large-scale additive manufacturing and microfabrication methods is likely to lead to a substantial decrease in production costs. With the maturation of these technologies, it becomes increasingly possible to directly incorporate biomimetic textures into structural components, without the need to apply them as additional coatings or retrofit them. The interplay between materials science, fluid mechanics, and bio-inspired engineering continues to provide greater opportunities and to enable the shift of experimental research toward practical, large-scale applications in transportation and energy systems.

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