# A Review on Aerodynamic Effects of Surface Texturing in Sports and Engineering

Siqi Shi [1], Jiaqi Zhang [2, *]

[1] Shanghai Thomas School, Shanghai, 200001, China

[2] Shanghai United Internation School (Gubei Campus), Shanghai, 200011, China

* Corresponding Author Email: jackyzhang0926@sina.com

**Abstract.** This template mainly focus on the relationship between the surface texture and the aerodynamic performances both in sports field and engineering field. There are several parts this essay is going to mention about. For example, different depth of the dimples in the golf ball could lead to different pressure difference and delayed separation. What is more, the composite material called aluminum alloy can be employed to the airfoils so that they can not only be lighter but also decrease most of the air resistance. Lastly, there is also a cross-scale contrast between the golf dimples and the airfoil leading edge in order to figure the common factors of successful design. The approach we use in the research is literature research method. The result of our research is that a successful design needs to consider about addressing the specific challenges of low speed, high angles, or efficient cruise in order to reach high stability and lower resistance during the movement.

**Keywords:** Laminar Flow, Airfoil Leading Edge Roughness, Golf Ball Dimples, Surface Texture.

## 1. Introduction

The design of surface textures is very important in aerodynamics. It can change how fluids move around objects. The design of golf balls and aircraft wings may seem unrelated at first glance, yet they share common aerodynamic principles that operate at different scales [1]. Both face the challenge of managing airflow to reduce drag and improve performance. However, the importance of certain factors like surface characteristics and material flexibility changes significantly with Reynolds number and angle of attack.

At low Reynolds numbers, such as those typical in golf ball flight, the flow around the object is more sensitive to surface texture. A smooth sphere would experience early flow separation, resulting in high pressure drag [2]. The dimples on a golf ball are designed to trip the boundary layer, making it turbulent. This delays separation and reduces the wake size, allowing the ball to travel farther. For small unmanned aerial vehicles or slow-flying gliders, similar principles apply. Surface roughness or riblets can be used to improve aerodynamic efficiency when operating at low Reynolds numbers. Conclusively, in this case, minute surface is even more principal than the general deforming shape.

In contrast, when operating with great attack angles, both airfoils and golf balls are improved due to the adaptability. For a golf ball, which is often hit with backspin, the deformation of the cover material influence how the dimples interact with the flow. Smoother materials can enable slight alternations in dimple shape to be under load, potentially maintaining better attachment to the air during steep climb or descent periods. As for wings, especially in natural flyers such as birds or in advanced morphing wing designs. Flexibility is the most important factor during flying. With high angles of attack, a rigid wing often stalls abruptly. But a flexible construction can alter its arch curvature or twist slightly, delaying stall and optimizing lift. This implies that when flow separation turns to a vital issue, the capability of a cover to adapt its shape can be more important than a static geometry.

The scope of operation also causes different design priorities. Golf balls are small and operate at speeds and sizes where surface details matter greatly. Wing design, especially for greater aircraft, are related to higher Reynolds numbers where general planform, thickness allocation, and sweep are more common. In a nutshell, the interaction between the body of the vehicle and the air follow the same physical laws, just demonstrated in two distinct physical way.

Material choice also reflects these functional demands. Golf ball covers use urethane or surly blends that offer a balance between durability and deformability. Modern aircraft might incorporate composite materials or smart structures that can alter their shape in response to flight conditions. In both, the trend is toward more responsive designs rather than purely rigid forms.

What connect these two fields is the need to manage flow separation—whether by roughing up a surface to energize the boundary layer at small scales, or by allowing the structure to adapt its shape at high angles of attack [1]. The optimization methods may differ due to scale and context, but the fundamental goals remain similar: reduce drag, increase lift, and maintain stability.

In conclusion, the comparison between golf balls and airfoils illustrate how aerodynamic design principles are applied across scales. Low Reynolds number conditions emphasize the role of surface characteristics, while high angle of performance require greater attention to material compliance and shape adaptation. Understanding these connections can inspire innovative solutions in both sports engineering and aerospace design.

This review looks at three examples: golf ball dimples, biomimetic surfaces like shark skin, and aircraft wing roughness. They all use similar ideas to control airflow, reduce drag, and improve performance. This paper discusses the common aerodynamic effects between them.

## 2. Golf Ball Design

### 2.1. Golf Ball Dimples

A golf ball is not smooth. It has many small dimples on its surface (FIG. 1). People might think a smooth ball has less air resistance and flies farther. But science show that a rough golf ball has half the drag of a smooth one and can fly up to five times farther [1,2].

**Figure 1.** Golf surface from https://pixabay.com/

The dimples assist the ball through two primary mechanisms. In terms of information introduction, they reduce pressure drag. Regarding the characteristics of the information, when air moves around a smooth ball, it separates early and generates a large low-pressure wake behind the ball. This results in a significant pressure difference between the front and rear areas, leading to high drag. The dimples cause the air layer (the boundary layer) to adhere to the ball's surface for a longer duration [1]. This delays air separation, resulting in a smaller wake and lower pressure drag. In terms of engineering application, the dimples induce an early transition to turbulent flow [3]. Concerning the advantages of the information, turbulent flow possesses greater energy and can remain attached to the ball's surface longer than laminar flow, which further contributes to delayed separation.

### 2.2. Biomimetic Surfaces

Shark skin is covered with tiny grooves called riblets (FIG. 2). These grooves reduce drag when the shark swims. Scientists copy this structure to make biomimetic surfaces for engineering, like on airplanes or ships.

The grooves on shark skin work by controlling the turbulence very close to the surface. They make the fluid flow in a certain way, reducing how much the fluid rubs against the surface (friction drag). Studies show that these grooved surfaces can make the flow calmer and have lower shear stress, which means less drag. Sometimes, these surfaces are also hydrophobic (water-repelling). Air pockets can get trapped in the grooves. This changes how the liquid touches the surface, making it like a mix of solid, liquid, and gas. This reduces wetting and can further reduce drag. The best shark skin patterns can reduce drag by up to 18.6% in water compared to a smooth surface.

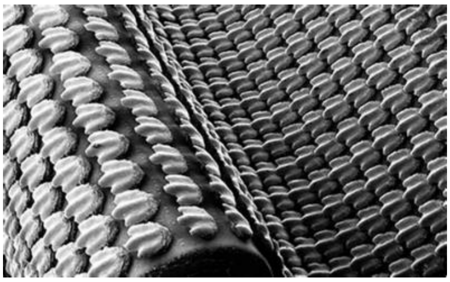

**Figure 2.** Shark skin surface from https://tech.huanqiu.com/

## 3. Aircraft Wing Softness

The roughness on an aircraft wing's surface can change how air flows over it. While too much roughness is bad, a carefully designed rough surface can be good. Generally, the chart below (Table 1) indicates this case:

**Table 1.** Aerodynamic Characteristics of Different Surface Roughness Types

| Roughness | Description | Effect | Main Benefit and Drawback | Where It Use |
|---|---|---|---|---|
| Hydrodynamic Smooth | Surface is very smooth; roughness height is much smaller than the boundary layer thickness, e.g., precision composite wings. | Transition point is delayed due to natural instability; larger laminar region. | Advantages: Lowest skin friction drag. Disadvantages: Highly sensitive to contamination or damage. | Gliders, some UAVs, wings designed for laminar flow. |
| Distributed | Many small roughness elements of similar size, e.g., sandblasted or corroded surfaces. | Acts as a trip device; triggers rapid transition to turbulence. | Advantages: Improves flow stability and predictability; prevents sudden separation. Disadvantages: Significantly increases skin friction drag. | Often used in wind tunnel tests to fix transition place. Usually not wanted on real aircraft. |
| Discrete | deliberately placed elements with specific shape and spacing, e.g., zigzag tape, vortex generators. | Gener controlled vortices; enhances mixing within the boundary layer to promote transition. | Advantages: Effective in delaying flow separation; improves lift and stall characteristics. Disadvantages: Increases both pressure and skin friction drag. | On wing leading edge for control separation; on fin root for better rudder effect. |
| Critical | Roughness height is sufficient to trigger transition without significantly increasing drag; an important design parameter. | Under optimal conditions, fixes transition location with minimal drag penalty. | Advantages: Ideal balance between flow control and drag. Disadvantages: Difficult to design and maintain; performance varies with Reynolds number. | More a design idea, not a real specific type. |
| Excessive | Large, irregular protrusions, e.g., ice accretion, deep dents. | Immediate boundary layer separation; transitions in shear layer, highly unstable flow. | Advantages: None. Disadvantages: Sharp increase in drag; loss of lift; degraded handling; may induce stall. | Dangerous condition. Must avoids during flight. |

For example, putting small rough elements on a wing can trip the boundary layer, making it change from smooth (laminar) flow to turbulent flow sooner. A turbulent boundary layer has more momentum and is better at fighting against adverse pressure gradients [1]. This means the air flow separates later than it would on a smooth wing. Later separation reduces the pressure drag. This is similar to how golf ball dimples work. Engineers can use this knowledge to place rough patches on wings to control where separation happens, improving lift and stall characteristics. These three different designs share some common aerodynamic strategies. Firstly, about controlling transition, they all can cause the boundary layer to transition from laminar to turbulent flow earlier than on a smooth surface [1]. A turbulent boundary layer is more resistant to separation. The main goal is often to reduce total drag. For golf balls and shark skin, the reduction in pressure drag is more significant than any potential increase in skin friction drags, leading to a net drag reduction. Besides, by energizing the boundary layer and making it more stable, these surface textures help the airflow stay attached to the surface for a longer distance [3]. This reduces the size of the wake, which is a major source of drag for bluff bodies like golf balls, and improves lift for wings. In some cases, these surfaces can interact with other effects. For example, a rotating golf ball or a spinning projectile with surface features might experience a Magnus effect more strongly [4]. The Magnus effect is a force perpendicular to the flow direction caused by rotation; it can be influenced by how the surface texture affects the boundary layer.

## 4. Materials Applied for the Aircrafts and Their Corresponding Properties

In aircraft field, material properties are closely related to the aerodynamic performance of aircrafts.

Taking aluminum alloy as an example [5]. Compared to conventional RF structures, TPMS lattices, which made of aluminum alloy, had greater convective heat transfer regions and more complicated inner configurations, which promote the frictional resistance of the fluid. These characteristics led to distinct flow vortices and huge flow resistance for TPMS lattices. The pressure gradient of TPMS lattices followed a quadratic relationship with flow velocity, satisfying the Darcy–Forchheimer law. Among the three TPMS lattices, the NW lattices had the highest permeability and the lowest resistance coefficient. As the volume fraction increased, the permeability declined and the resistance coefficient grew.

**Table 2.** Wing Performance Parameter Table

| Property | Value |
|---|---|
| Wing mass | 16,920 kg |
| KS (FI), upper skin | 0.945 |
| KS (FI), lower skin | 0.985 |
| KS (FI), aluminum spars | 0.959 |
| KS (FI), aluminum ribs | 0.856 |
| KS (FI), aluminum spar caps | 1.007 |
| KS (FI), aluminum stringers | 1.000 |
| First buckling eigenvalue | 1.492 |
| Flutter speed | 274m/s |

For Table 2 given above, it is quite obvious that the mass of the wing made of composite materials are relatively smaller than those made of conventional materials [6]. Taking the experiment about the single-target optimization problem of the minimization mass of the wing. We used traditional UD composite material for the wing surface. Then, the remaining optimization problems are summarized in Table 3 below.

**Table 3.** Wing Optimization Constraint Condition Table

| Constraint Type | Limit Value |
|---|---|
| KS (FI), composite skins | ≤1 |
| KS (FI), aluminum spars | ≤1 |
| KS (FI), aluminum ribs | ≤1 |
| KS (FI), aluminum spar caps | ≤1 |
| KS (FI), aluminum springers | ≤1 |
| First buckling eigenvalue | ≥1.5 |
| Flutter speed | ≥1.2*V dive |

The appliance with the composite and smooth material and deformable surface provide new probability for the aerodynamics of the aircraft. They can achieve the effect of decreasing the air resistance through passive or active ways [7]. They can achieve the effect of decreasing the resistance through passive or active ways. For example, most of the drive systems for deformable wings are powered by hydraulics or electric motors, which can generate large actuation forces. However, its complicated structure and large size do not alleviate the vehicle to optimize mobility. As a fresh sort of material coordinating sensing and driving, advantages of high power-to-weight ratio, temperature sensitivity, lower driving voltage, simple driving structure, and favorable driving process are carried by SMA. Actuators made of shape-memory alloys are employed to the deformable wings of small, unmanned aircrafts. A deformable wing with actuators is bale to promote the aerodynamic performance of the vehicle. SMA actuators show their pros of simple construction, high deformation efficiency, and lightweight in changing the shape of the wing, which fits particularly for the research and enhancement of the deformable wing of small unmanned aircrafts.

The effect of the surface coating cannot be overlooked. Hydrophobic and water-resistant coatings can reduce the attachment of water vapor on the surface of aircraft, preventing airflow disturbances caused by water vapor; low-energy surface coatings not only affect the development of the boundary layer, delaying boundary layer separation, but also own anti-pollution capabilities, reducing the negative effects of dust and other contaminants on the aerodynamic characteristics of aircraft and achieving better aerodynamic performance.

Conclusively, different materials with their correlated properties, affects the aerodynamics performance of the aircrafts form different metrics. The moderate application of these materials plays an indispensable role in the development of the aviation technology and performance promotion. This can lead to enhancement of flying efficiency, stability and economics.

## 5. The Influence Caused by the Airfoil Shape

Turning to the stall performance of the air, the key factors of this are the shape of the figures of the wings and the high lift configuration [8]. Specifically for the airfoils: The current study pays delves into promoting the aerodynamic characteristics of airfoils for tiny wind turbines in developing countries, where low Reynolds number (*Re*) flow conditions usually lead to laminar separation. Two new airfoils, INDTH7 (thin) and INDTH12 (wide) were designed specifically for Indian environmental conditions and experimented in online models. These airfoils were contrasted with NACA2408 and SD6060, commonly employed in low *Re* applications. Results show that the airfoils INDTH7 and INDTH12 outperformed existing ones, with higher lift-to-drag ratios and stall angles. The optimum lift-to-drag ratios for INDTH12, INDTH7, NACA2408, and SD6060 were 112, 101, 87, and 94, respectively. The power coefficient and tip speed ratio performance of the INDTH7 and INDTH12 airfoils differed significantly from existing ones, while INDTH12 reaches a peak power coefficient of 0.551 at TSR 5, and INDTH7 reaching 0.556 at TSR 8. Additionally, there were minimal variations in lift performance for INDTH7 and INDTH12, enabling them to be suitable for low *Re* applications. These airfoils, improved with a thickness-to-camber ratio ($t/c$) between 0.875 and 3.5, resolving the issue of laminar separation in tiny scope of wind turbine blades, promoting overall performance in household energy generation systems. The new airfoils were studied computationally using Ansys Fluent for turbulent, two-dimensional, steady, incompressible fluid flow. Additionally, in a high lift configuration, when the leading edge of the wing are extended, they can make high-speed airflow over the upper wing surface, delaying flow separation; when the trailing edge are lowered, they increase the camber of the wing, enhancing lift, while also increasing the wing area to strengthen aerodynamic effects. The combination of the two can significantly improve the lift of the aircraft during takeoff and landing phases, enhance aerodynamic performance, and ensure flight safety and efficiency.

## 6. Comparison across Metrics

Turning to the cross-scale comparison. There are several similarities and differences between the principles of the golf ball dimples and the airfoil leading edge roughness. Firstly, the similarities of these two designs are the objective. They both actively or passively change the fluid state in order to achieve the control of the aerodynamics characteristics. The principal mechanism is mainly about promoting turbulent flow and finally eliminate the resistance as much as possible. In terms of the golf ball, the dimples of the ball enlarge the time of the air staying on the ball in order to lower the pressure drag. Additionally, the dimples also cause early stage of transition so that the transition flow has more energy to stay attached to the ball which also helps delay separation [9]. A flight tracing experiment was launched based on the obtained experimental results, and the impacts of the dimple occupancy and dimple volume ratio on the flight distance were illustrated. When comparing these two depths, the lift-drag ratio was about 15% lower for greater dimples. Regarding the dimple volume ratio, the drag coefficient grew with increasing dimple volume ratio. The lift-drag ratio was also highest in the dimple volume ratio range of $11.0–12.0 \times 10^{-3}$ [10]. As for the airfoil leading edge roughness, couples of researches have been conducted on the effects of aerodynamic characteristics of airfoils with leading-edge modifications such as adding roughness, waves, and so on, which have caused favorable variation in aerodynamic characteristics. This led to the contemporary study, which is related to a new passive flow control technique that has a separated roughness element in the form of an emery sheet, placed on the suction side of the airfoil with a region covering about 50% chord from the trailing edge of the airfoil. An experimental analysis of the modified NACA 0015 airfoil was also shown in the low subsonic wind tunnel situated at SASTRA Deemed for the free stream Reynolds number of $2.04 \times 10^5$ at angles of attack ranging from 0° to 45°. An advanced device called multichannel Ethernet-Based Simultaneous Pressure Scanner was applied to calculate the surface pressure of the airfoil, which was further processed for observing aerial performance. The static behavior has been changed by the increase of a roughness material at the flow transition section on the cover of the wings. This in turn decreases the impacts of the contrary pressure gradient at critical and post-critical angles of attack, leading to turbulence kinetic energy at the transitional boundary layer, promoting an attached flow and a delay in the stall. Adding roughness material at the trailing cover of the airfoil has mainly had an extreme impact on the aerial performance, which may decline the influence of dynamic stalls, resulting in paving the way for the design of an efficient wind turbine blade.

However, there are still some differences. Specifically, the ways the golf ball dimples and the airfoil leading edge roughness producing the lift force are distinct. For the golf ball dimples, they cooperate with the spin and produce huge amount of drag force [11]. In terms of spinning balls, it is easy to explain the ratio of the angular velocity to the linear velocity using the non-dimensional spin factor, *S*, defined by where $\omega$ is the velocity with angle, and *r* is the radius length of the ball. Due to the backspin, the top section of the ball is moving along with the air flow, while the bottom part of the ball is moving against the air flow. The relative air-to-ball surface speed on the top and bottom of the ball is, as a result, lower and higher than the ball speed, respectively. Backspin causes flow on the top side to separate further from the stagnation point, while flow on the bottom side separates towards to the stagnation point. The rotated stagnation points (relative to the ball center) cause a vertical pressure gradient, producing an upward force and the Magnus effect. To put it in real life situation, one experiment has displayed a negative lift force on a sphere with backspin, referred to as the reverse Magnus effect. When the ball is traveling nearer to the speed where the boundary layer becomes turbulent, backspin is able to cause the top side of the ball to have laminar flow, while the bottom boundary layer is turbulent. The laminar flow on the top surface moves the separation point forward, influencing the direction of the Magnus effect downward, producing the oppose Magnus effect. While the golf ball utilizes the spin, the airfoil leading edge roughness delays the moment of separation in order to produce the drag force passively. As mentioned above, the excessive roughness causes immediate boundary layer separation. Discrete roughness works outstandingly to delay flow separation, makes more lift, better stall [12]. In several simulating experiments, the computations used ideal microgrooves with an absolutely smooth surface. In other words, the texture of cover, pattern and material cooperate together to influence greatly on the aerodynamic performances of the airfoil [13]. In the low-Reynolds-number approach, the aerodynamic characteristics about a static object differ from those observed at the scope of passenger-airplanes. Hence, the improved wings and pattern alter with vehicle size. Followed by the modification of the vehicle dimensions, non-proportional scaling between surface regions and weight shifts the dominance of physical maneuverability, leading to distinct operational parameters and technical tasks. With smaller aircrafts, structural flexibility as well as anisotropic material properties become more remarkable, which leads to qualitative changes in aerodynamics. The flapping movement of the wings, the interactions between wings, the collaborative characteristics of wing and tail, and the optimization of soft structures for more optimized flexibility and aerial characteristic are discussed, which collaboration innovation are required by low Renolds-number to majorize pattern, material along with surface in accordance with the scaling laws. Collaboratively, progress on these fronts is reforming the design paradigm of those aircrafts while other types of robots with shrinking physical dimensions and even more diversified capabilities to meet wider ranges of requirements. The design of golf balls and aircraft wings may seem unrelated at first glance, yet they share common aerodynamic principles that operate at different scales. Both face the challenge of managing airflow to reduce drag and improve performance. However, the importance of certain factors like surface characteristics and material flexibility changes significantly with Reynolds number and angle of attack.

At low Reynolds numbers, such as those typical in golf ball flight, the flow around the object is more sensitive to surface texture. A smooth sphere would experience early flow separation, resulting in high pressure drag. The dimples on a golf ball are constructed aiming to trip the boundary layer, making it turbulent. This approach postpones separation and decreases the size of the wake, enabling the ball to travel for farther distance. In terms of small unmanned aircrafts or slow-flying gliders, similar principles are employed to those transportations. Surface roughness or riblets can be utilized to promote aerodynamic efficiency when operating at low Reynolds numbers. Conclusively, in this case, minute surface features play a more vital role than general shape deforming process. In contrast, when operating with high attack angles, both airfoils and golf balls are optimal from adaptability. As for a golf ball, which is often hit with backspin, the deformation of the cover material affects how the dimples interact with the air flow. Smoother materials can lead extreme tiny alternations in dimple pattern under load, probably maintaining better airflow attachment during steep climb or descent periods. Among varieties of airfoils, especially in natural flyers like birds or in cutting-edge morphing wing constructions, flexibility is the most pivotal factor. At high attack angles, a rigid wing often stalls all of a sudden. But a compliant structure can alter its camber or twist smoothly, delaying stall and optimizing lift. This demonstrates that when flow separation becomes a major issue, the capability of a surface to adapt its pattern can be more vital than a static geometry. The scope of operation also causes distinct design priorities. Golf balls are little and operate at speeds and sizes where surface details matter tremendously. Wing design, especially for larger aircraft, operating with higher Reynolds numbers where general planform, thickness distribution, and sweep are more prominent. In both two situations, the relationship between the body and the air follow the same physical principles are demonstrated differently.

Options about material also implies to these functional requirements. Golf ball covers use urethane or surlyn blends that provides with a balance between durability and deformability. Modern aircraft might combine composite materials or flexible structures that can alter their shape in response to flight situations. In both, the trend is toward more responsive designs rather than purely rigid forms. Flow separation is needed to manage the airflow, whether by roughing up a surface to energize the boundary layer at tiny scales or by enabling the structure to alter its shape at high angles of attack. The improvement approaches may be distinct from each other due to scale and background, but the fundamental goals remain similar: reduce drag, rising lift, and maintain stability. In a nutshell, the contrast between golf balls and airfoils illustrate how aerodynamic construction laws are utilized among metrics. Low Reynolds number conditions focus on the role of surface characteristics, while greater attention to material compliance and shape adaptation are required by high angle of performance. Understanding these connections can inspire advanced methods in both sports engineering and aerospace field.

## 7. Conclusion

Conclusively. As for the discussion about different material properties and aerial characteristics, the key is on how conventional materials such as aluminum leads to surface smoothness for efficient flying process, while new submissive materials can alter their pattern to delay stall and decline drag through various approaches either in active or in passive way. It also describes how special coatings, for example hydrophobic ones, can helps manage the boundary layer and prevent issues like ice accumulation, which is crucial for maintaining performance. Turning to the relationship between geometry and flight performance, this part compares the flight of balls such as golf, soccer and cricket, where spin and geometry create aerodynamic forces, to the design of wings where aspects like aspect ratio and leading-edge shape determines stall behavior. It also outlines how high-lift devices such as slats and flaps on aircrafts alters the wing's geometry to dramatically improve performance during take-off and landing. There are also completed analysis and cross-scale comparison of between the golf ball dimples and the airfoil leading edge roughness. The comparison between the role of golf ball dimples, which triggers transition to reduce drag, with wing leading-edge roughness, which might be used to delay separation through pointing out their different purpose despite a similar method are shown firstly in the analysis. It argues that no single factor can make a huge difference. Instead, the improved performance stems from the collaboration of cover, material, and shape, with each becoming most vital under specific conditions like lower Reynolds number, high attack angles, or high-speed conditions.

The study also reveals a common principle: the intelligent management of airflow. The key takeaway is that the effectiveness of surface textures, material adaptability, and overall geometry is not absolute but highly dependent on the flight conditions. A successful design therefore requires a harmonious integration of all three aspects, choosing the right combination to address the specific challenges of low speed, high angles, or efficient cruise. This cross-scale understanding allows engineers to draw inspiration from nature and sports to innovate in aerospace, and vice versa.

## Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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