Proceedings of the 4th International Conference on Applied Physics and Mathematical Modeling
DOI: 10.54254/2753-8818/2026.37895

Biomimetic Applications in the Aerodynamic Shape Design of Aviation and Automotive Vehicles

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Abstract. Biomimetic aerodynamic design draws inspiration from biological structures and flow-control mechanisms to improve the aerodynamic performance of aircraft and automobiles. This paper reviews representative biomimetic concepts, including humpback-whale leading-edge tubercles, shark-skin riblets, boxfish-inspired body shapes, dragonfly-wing corrugations, and bird-inspired wingtip structures. The discussion focuses on how these designs influence drag reduction, lift enhancement, flow-separation control, and stability under specific operating conditions. A conditional cross-domain comparison is conducted between aviation and automotive applications in terms of Reynolds number, dominant drag source, operating conditions, scaling effects, manufacturing difficulty, surface durability, and engineering maturity. The review shows that the effectiveness of biomimetic structures is highly condition-dependent and that laboratory-scale benefits cannot be directly transferred to full-scale engineering systems. Supporting technologies, including computational fluid dynamics, advanced manufacturing, and machine learning, are also examined. Major challenges include scale mismatch, operating-condition migration, surface contamination, durability, manufacturability, and cost. Future research should move from direct form imitation toward mechanism-based biomimetic design, while integrating aerodynamic performance with structural, manufacturing, and economic constraints. More rigorous benchmarking and full-scale validation are required to bridge the gap between experimental studies and practical engineering applications.

Keywords: Biomimetics, Aerodynamics, Shape design, Drag reduction, Aviation, Automotive

1. Introduction

Aircraft and ground vehicles face several core problems in shape design. These problems include reducing aerodynamic drag, optimizing lift characteristics, delaying flow separation, and ensuring operational stability. These indicators directly affect fuel consumption, range, and emissions. A literature review indicates that beetle-inspired design has the potential to reduce automobile drag by about 16% [1]. In aviation, riblet films on fuselage surfaces can reduce friction drag by about 6% [2]. Traditionally, engineers rely on empirical formulas and parameter sweeps for shape optimization. However, these methods show limitations when flow problems become complex.

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DOI: 10.54254/2753-8818/2026.37895

Researchers then turned to nature. Biological forms evolved over millions of years may bring new solutions.

Biomimetics extracts design principles from biological structures, functions, and behaviors. It then converts them into engineering solutions. In aerodynamic shape design, many cases can be used for reference. The tubercles on the leading edge of humpback whale flippers can delay stall at high angles of attack [1]. Micron-scale grooves on shark skin can reduce friction drag in turbulent boundary layers [3, 4]. The boxfish has a box-like shape. This shape does not look streamlined. However, its model drag coefficient is surprisingly low in some wind tunnel tests [5-7]. The corrugated structure on dragonfly wings can control flow separation by inducing tiny vortices . These natural aerodynamic optimization schemes have shown good potential in laboratory conditions. Some technologies have even moved from the laboratory to engineering validation [8-10].

However, aircraft and cars differ greatly in physical conditions and engineering constraints. Both seek drag reduction and lift enhancement. Aircraft cruise Reynolds numbers are usually on the order of 10^6–10^7. This is based on mean aerodynamic chord. The Reynolds number range for cars is wider. If vehicle length is used as the characteristic length, a highway condition at about 30 m/s corresponds to $Re \approx 4.5\times10^6$. Aircraft design cares most about lift-to-drag ratio at cruise. Cars must perform acceptably in urban, suburban, and highway conditions. Cars must also consider crosswind stability, cooling ventilation, and driving noise. The same biomimetic structure may work well on an aircraft. It may not work on a car. It may even have a negative effect. This point is discussed in Chapter 5.

Research on biomimetic aerodynamic design is increasing. However, most works focus on a single biological model. Some works are limited to one type of vehicle. Reviews that compare aviation and automobiles together are rare. This paper is a narrative review. It aims to integrate representative research results from existing literature. It summarizes main findings and identifies research gaps. The main line is how bio-inspired shapes and surfaces improve aerodynamic performance. This paper first introduces basic concepts and common biological models. It then reviews representative applications in aviation and automobiles. It focuses on the conditions under which each biomimetic structure is effective. It also focuses on the benefits that can be achieved. On this basis, this paper compares the two fields. The comparison covers Reynolds number, drag source, target operating conditions, scaling effects, manufacturing difficulty, surface durability, and engineering maturity. Finally, this paper introduces supporting technical tools. It discusses current challenges and possible future directions. Structural lightweighting and materials are mentioned only when directly related to aerodynamic performance.

2. Basic concepts of biomimetic aerodynamic design

Biomimetics is an interdisciplinary field. It draws inspiration from biological structures, functions, and evolutionary strategies. It then converts them into engineering design. In aerodynamic shape design, the basic logic is as follows. Organisms are repeatedly screened by fluid environments over a long evolutionary process. They develop a set of shapes and surface features. These features represent an optimization direction to some extent. Engineering design can use them as references.

From the perspective of aerodynamic performance, biomimetic design usually aims at four goals. The first is drag reduction. This includes friction drag and pressure drag. The second is lift enhancement. This means a wing or similar structure produces more lift under the same conditions. This is especially important at high angles of attack. The third is delaying flow separation. This makes the boundary layer stay attached longer. It reduces the wake region. It also reduces pressure

DOI: 10.54254/2753-8818/2026.37895

drag. The fourth is improving stability. This makes aircraft or vehicles more stable and controllable in complex flow fields.

In practice, common inspiration sources can be grouped into four categories. Leading-edge biomimetics is the first. The most typical example is the tubercles on the leading edge of humpback whale flippers. Periodic undulations are introduced at the leading edge of an airfoil. This changes the generation and evolution path of leading-edge vortices. It then affects stall characteristics. Surface microstructure biomimetics is the second. The representative is shark skin riblets. Micron-scale grooves can change near-wall vortex structures in a turbulent boundary layer. This reduces friction drag. Overall shape biomimetics is the third. The most famous example is the boxfish. Its overall shape is used to optimize pressure distribution. This reduces pressure drag. Local component biomimetics is the fourth. An example is the corrugated surface of dragonfly wings. Micro-scale geometric features induce controlled vortices. These vortices are used for flow separation control.

Aviation and automobiles share the same direction in biomimetic strategies. However, their specific constraints and evaluation criteria differ. Aviation design pursues cruise efficiency. It aims for optimal performance at a specific speed and altitude. Automobiles must perform acceptably under many conditions. They also have requirements for crosswind, cooling, and noise. This means a biomimetic scheme must be checked before use. Its effective conditions must be clear. Its failure conditions must also be clear. These conditions often vary with specific studies. They must be judged with the original literature.

3. Biomimetic aerodynamic design applications in aviation

3.1. Leading-edge biomimetics: humpback whale flipper tubercles

The scalloped tubercles on the leading edge of humpback whale flippers are one of the most discussed cases in biomimetic aerodynamic design. Miklosovic et al. conducted wind tunnel experiments in 2004. They showed that adding leading-edge tubercles to a scaled whale flipper model delayed the stall angle by about 40%. Lift increased and drag decreased [1, 8]. van Nierop et al. further explained this phenomenon in 2008 with a theoretical model. They pointed out that the tubercles delay stall by generating streamwise vortices. Stall delay is not sensitive to tubercle wavelength [3].

It should be noted that the experiments by Miklosovic et al. were done on a scaled model. They were not full-scale aircraft validation [1, 8]. The observed stall delay of about 40% is a result under specific model geometry and experimental conditions. It cannot be directly equated with a general rule for any airfoil or any condition. Some studies measured a stall angle delay from 8° to 15° under specific conditions. They also measured a maximum lift coefficient increase of about 22%. However, these values only represent results under that specific experimental setup [3]. Tubercles may slightly reduce lift at low angles of attack. Therefore, their benefits mainly appear at high angles of attack or post-stall conditions [3]. When considering their use on commercial aircraft main wings, the cruise-phase benefit must be carefully evaluated. It must be weighed against increased manufacturing complexity.

From single-study observations, tubercles are effective at Re ≈ 180,000 and within a specific angle-of-attack range. As the angle of attack increases further, separation is still delayed. However, overall lift begins to decline. For engineering translation, this idea has been tried on wind turbine blades and unmanned aerial vehicle wings. However, large commercial aircraft main wings rarely use it so far.

DOI: 10.54254/2753-8818/2026.37895

3.2. Surface microstructures: shark skin riblets

Shark skin is covered with micron-scale riblets aligned in the flow direction. Their mechanism is to suppress spanwise vortex motion in a turbulent boundary layer. This reduces wall friction drag. Numerical simulation studies show that a maximum drag reduction of about 9.46% can be achieved. This happens when the dimensionless riblet spacing s^+ is between 15 and 20. The tip angle is about 30°. The s/h ratio is 2. It should be noted that 9.46% is a numerical simulation result for flat-plate boundary layer flow. It is not measured data from a real aircraft.

Shark skin riblets are one of the few biomimetic technologies that have achieved engineering application. In aviation, the German Aerospace Center and Airbus collaborated. They applied riblet films to the fuselage surface of A320 series aircraft. Tests showed that friction drag was reduced by about 6% [10]. It must be emphasized that a 6% friction drag reduction is not equal to a 6% total drag reduction. Friction drag is only part of total drag. The actual improvement in overall fuel consumption is usually smaller than the friction drag reduction percentage. Airbus public materials show that A320 with AeroSHARK riblet technology can save about 1%–2% in fuel consumption [10]. China's Y7 aircraft also reported about 8% drag reduction after applying a streamwise grooved surface. The specific meaning of this data must also be noted. It must be clear whether it is friction drag or total drag.

The applicable condition is that the flow direction must be basically aligned with the grooves. The s^+ value must remain in the 15–20 range. The failure condition is that surface contamination, wear, or increased flow yaw angle can significantly weaken or even reverse the drag reduction effect. When the flow yaw angle exceeds a certain range, riblets may increase drag instead of reducing it [5]. This flow direction sensitivity becomes a fundamental constraint in automotive applications. This is discussed in Section 4.3.

3.3. Wingtip biomimetics: bird wingtip feathers and multi-winglets

The split feather structure at bird wingtips can weaken wingtip vortex strength. This reduces induced drag. This principle is similar to the design idea of modern winglets. However, it must be explained. Modern winglets were mainly developed by Whitcomb et al. in the 1970s. They were based on aerodynamic theory. They were not directly copied from birds [11]. A more accurate statement is as follows. The flow control mechanism of bird wingtips provides a biological reference for understanding wingtip vortex weakening. However, the geometric parameters of engineering winglets are mainly optimized by aerodynamic calculation and wind tunnel experiments [12].

In recent years, some researchers proposed biomimetic multi-winglet designs. These designs are based on bird wingtip feathers. They aim to split a single large wingtip vortex into multiple small vortices. This reduces induced drag [13-15]. This belongs to mechanism-similarity biomimetics. Lee and Sarigul-Klijn (2026) showed that the wingtip gap distance is the most critical parameter in multi-winglet design. Optimal performance can be obtained when the gap is close to the local wingtip chord [15]. These studies are still in the numerical simulation and concept validation stage.

3.4. Other typical applications

Besides the three categories above, aviation has other biomimetic aerodynamic explorations. These include noise reduction designs inspired by the serrated trailing edge of owl wings. They also include variable camber wings inspired by seagull wing morphology. Most of these remain at the laboratory stage. They are still far from engineering application.

DOI: 10.54254/2753-8818/2026.37895

4. Biomimetic aerodynamic design applications in automotive exterior design

4.1. Overall vehicle shape biomimetics: the boxfish

The boxfish (Ostracion cubicus) is a fish that lives in tropical coral reefs. Its shape is approximately a box. Its aerodynamic characteristics have important inspiration for biomimetic design research.

Mercedes-Benz engineers tested an accurate model of the boxfish in the Stuttgart wind tunnel. They measured a drag coefficient of 0.06 [7]. This data attracted wide attention in 2005. It directly led to the development of the Mercedes-Benz Bionic Car concept [8]. However, later studies questioned this value. Some studies used wind tunnel experiments and CFD methods to systematically study boxfish models. Results showed that the boxfish drag coefficient is about 0.2–0.24. This is closer to the 0.19 of the Mercedes concept car [2, 7]. This numerical difference reminds us of something. The 0.06 value is not an inherent drag coefficient of the boxfish shape. It may be a result measured under specific model accuracy and specific wind tunnel conditions. Data from different experimental systems cannot be directly equated.

In 2005, Mercedes-Benz launched a biomimetic concept car inspired by the boxfish [8]. Engineers first used a 1:4 clay model for wind tunnel testing. They measured a drag coefficient of 0.095 [11]. The full-scale four-seat drivable concept car had a measured Cd of 0.19 [8, 11]. This is about half of the contemporary Mercedes 300SE. For reference, the Honda Insight had a Cd of 0.25. The Toyota Prius had a Cd of 0.26.

The boxfish shape not only affected the aerodynamic contour. It also inspired body structure. The boxfish shell consists of hexagonal bony plates. It combines light weight and high strength [9]. Mercedes-Benz developed body panels based on this principle. The stiffness is reported to be significantly improved over traditional design. Weight is also reduced [8, 11]. For power, the car used a 103 kW direct-injection diesel engine. Fuel consumption was 4.3 liters per 100 km under the EU cycle.

However, several points must be noted when citing this case. First, the 0.06 value is highly controversial. It should not be repeatedly emphasized as a low-drag fact of the boxfish. A more appropriate approach is to present the boxfish case as a typical example of early biomimetic concept and later reinterpretation of its flow mechanism. Different literature reports Cd values of 0.06, 0.19, and 0.24. These differences reflect different experimental conditions, model accuracy, and test methods. The numerical difference cannot be simply attributed to scaling effects.

Second, recent research reveals the aerodynamic mechanism of the boxfish shape. Its low drag may not come from a traditional streamlined shape. It may be related to its sharp edge features. These edges can manipulate the wake structure. This reduces the overall drag coefficient [9]. This finding suggests that the low-drag mechanism of the boxfish may be more complex than it appears.

Third, the boxfish shape has excellent aerodynamic performance. However, its box-like structure has clear limitations in interior space utilization and styling acceptability. This may be one of the main reasons it was never produced. The tension between aerodynamic performance and commercial feasibility is a real problem for biomimetic design. It must be faced when moving from concept to production.

4.2. Local aerodynamic component biomimetics: dragonfly wings and vortex generators

Dragonfly wings have complex corrugated structures on both leading and trailing edges. Studies show that corrugated airfoils have higher lift and better stall resistance than smooth airfoils at low Reynolds numbers. Some studies conducted three-dimensional CFD simulations of dragonfly

DOI: 10.54254/2753-8818/2026.37895

corrugated airfoils. The Reynolds number was 80,000. The angle of attack was 0°–8°. Results showed that corrugated airfoils can generate leading-edge vortices and spanwise flow. These features do not appear on conventional smooth airfoils. It is worth noting that the corrugated structure adds some extra drag. However, the lift enhancement is more significant. The overall lift-to-drag ratio is still higher.

Inspired by this, researchers abstracted the corrugation features of dragonfly wings into a vortex generator design [12]. In automotive engineering, vortex generators have been used to control rear-body flow separation. They reduce pressure drag in the wake region [14]. The biomimetic contribution is providing geometric forms beyond traditional trapezoidal or rectangular vortex generators. Arcuate or wavy vortex generators inspired by dragonfly corrugations do perform better under some conditions [14].

However, it should be pointed out that the excellent aerodynamic performance of dragonfly corrugated airfoils is mainly shown at low Reynolds numbers. The related studies usually have Reynolds numbers between 10^3 and 10^5. The Reynolds number of typical automotive driving conditions is usually higher. This is based on vehicle length as the characteristic length. For highway conditions at about 30 m/s, the Reynolds number is higher. Therefore, when directly transplanting the dragonfly corrugation structure to automotive vortex generators, its effectiveness depends on specific conditions. Vehicle speed, local body curvature, and incoming flow turbulence intensity all affect the final effect. When the Reynolds number rises beyond its effective range, the benefit of the corrugated structure may weaken or even disappear.

4.3. Surface microstructures in automotive drag reduction

Shark skin riblets have also been explored in automobiles. Some studies applied riblets to a formula race car front wing. Wind tunnel experiments showed a 2.0% increase in lift-to-drag ratio [12]. Some reports say that applying a riblet surface to an electric vehicle above 90 km/h can reduce friction drag by 8%–10% [11]. It must be emphasized again that an 8%–10% friction drag reduction is not equal to an 8%–10% total vehicle drag reduction. Pressure drag dominates total vehicle drag. Friction drag accounts for far less than 100%. Therefore, the actual benefit of friction drag reduction at the vehicle level is much smaller.

Riblet technology has a fundamental constraint in automobiles. The drag reduction effect of riblets is highly sensitive to flow direction. The effect is best when the incoming flow is aligned with the grooves. Once the yaw angle exceeds the range, drag may increase [5]. Aircraft cruise has a relatively stable incoming flow direction. Riblets can align well. Cars experience continuously changing crosswinds. The steering wheel is constantly adjusted. The airflow direction relative to the body surface is always changing. In addition, a review clearly points out something. For objects like cars, pressure drag is the main drag source. Friction drag is not the main source. The application effect of riblets is very limited [11]. The drag reduction rate under laboratory conditions is often greatly reduced in real applications [11]. These factors together limit the promotion of riblets in production cars. Researchers have shifted the riblet idea to biomimetic non-smooth design at the bottom of tire longitudinal grooves. This improves tire hydroplaning performance [13]. This is a functional migration of the riblet principle from drag reduction to water drainage.

4.4. Other biomimetic aerodynamic design explorations

Besides the categories above, beetle body shape has been studied for automotive drag reduction. A literature survey shows that beetle-inspired design has the potential to reduce automobile drag by

DOI: 10.54254/2753-8818/2026.37895

about 16% [11]. This is a potential assessment in a literature review. It is not measured data. Biomimetic surface treatment and multi-element flow control concepts have also been incorporated into wheel aerodynamic drag reduction strategies [13]. These explorations show that biomimetic aerodynamic design in automobiles is extending from body shape to broader subsystems.

5. Comparative analysis of biomimetic aerodynamic design in aviation and automobiles

The previous two chapters introduced biomimetic applications in aviation and automobiles separately. This chapter puts them together for a conditional comparison. It must be emphasized that the following comparison is not a universal conclusion. It is based on specific typical scenarios. These scenarios are large commercial aircraft cruise and passenger car highway driving. Different aircraft types have very different mission profiles. These include fighters, unmanned aerial vehicles, and general aviation. Different vehicle types also have different mission profiles. These include SUVs, race cars, and commercial vehicles. Their flow conditions differ greatly. The related judgments should be understood with specific application scenarios.

Reynolds number range. The cruise Reynolds number of a large commercial aircraft is usually on the order of 10^6–10^7. This is based on mean aerodynamic chord. For a passenger car with vehicle length as the characteristic length, a highway condition at about 30 m/s corresponds to $Re \approx 4.5\times10^6$. The effective condition for humpback whale tubercles is $Re \approx 180{,}000$ [1, 3]. This is closer to a small unmanned aerial vehicle or a wind turbine blade. It is not close to large commercial aircraft cruise. The effective Reynolds number for dragonfly corrugations is 10^3–10^5. This corresponds to micro air vehicles. It is far below automotive and aircraft cruise conditions. This shows something. The performance of biological models under laboratory conditions cannot be directly extended to engineering scale. Reynolds number matching must be considered.

Main drag source. In large commercial aircraft cruise, friction drag accounts for a relatively high proportion of total drag. Therefore, riblet technology has a relatively clear effect under specific conditions. A320 measured friction drag reduction is about 6% [10]. Passenger cars are dominated by pressure drag. This is drag caused by low pressure in the body wake region. Friction drag accounts for a relatively small proportion [11]. However, both "large friction drag proportion" and "large pressure drag proportion" are relative concepts. Different aircraft types have different drag compositions. Different flight states also have different drag compositions. Different vehicle types have different drag compositions. Different vehicle speeds also have different drag compositions. Therefore, the observation that riblets work better on large commercial aircraft and less well on passenger cars should be understood as an induction based on specific scenarios. It is not a universal rule.

Target operating conditions. Large commercial aircraft pursue single-point cruise optimum. They aim for the best performance at a specific speed, altitude, and angle of attack. Passenger cars require acceptable performance under all conditions. These include urban commuting, suburban cruising, and highway driving. They also face crosswinds and lane changes. Their operating conditions are far more complex than those of commercial aircraft. Humpback whale tubercles are effective at high angles of attack. However, the benefit is not obvious at low cruise angles. It may even be negative [1, 3]. This "specific condition optimization" characteristic is relatively acceptable for commercial aircraft. This is because most time is spent at cruise. It is difficult to promote in passenger cars. This is because conditions change frequently. However, fighters pursue maneuverability rather than cruise efficiency. Unmanned aerial vehicles may operate under specific conditions for a long time. Their condition characteristics are completely different from commercial aircraft.

DOI: 10.54254/2753-8818/2026.37895

Scaling effects. In the boxfish case, the biological model Cd is 0.06 [7]. The 1:4 model Cd is 0.095 [8, 11]. The full-scale vehicle Cd is 0.19 [8, 11]. The three values differ significantly. However, it must be pointed out that these three data sets do not correspond to the same model with strict geometric similarity and identical boundary conditions. In addition, the 0.06 value itself is controversial. Therefore, the change from 0.06 to 0.095 to 0.19 should not be used as evidence of scaling effects. A more accurate statement is as follows. Results differ significantly under different scales and model conditions. This shows that scaled model experimental results cannot be directly extrapolated to full-scale vehicles.

Manufacturing difficulty and cost. Riblet films can be attached to fuselage surfaces. Manufacturing difficulty is relatively controllable [10]. Humpback whale tubercles require changing the wing leading-edge geometry. This involves mold modification and structural re-certification [3]. The complex curved surface of dragonfly corrugated vortex generators requires precision machining. In general, large commercial aircraft manufacturing has high single-product value and large drag reduction benefits. The sensitivity to unit cost is relatively low. Passenger car manufacturing has large production volume and thin profit margins. It is extremely sensitive to cost. However, the cost sensitivity difference between low-cost general aviation and luxury cars may be larger than the industry average difference between aviation and automobiles.

Surface durability. The micron-scale grooves of riblets are easily clogged by dirt. They are also easily damaged by wear [5]. Large commercial aircraft can be cleaned and maintained after each flight. Passenger cars face more complex surface environments. These include rain, snow, mud, and car washing. Riblets are difficult to maintain performance on passenger cars for a long time. This is an important reason limiting their promotion. However, not all aircraft can get the same maintenance conditions as large commercial aircraft. Not all cars have the same harsh operating environment.

Engineering maturity. Riblet technology has completed real-aircraft validation on the A320. Its engineering maturity is relatively high [10]. Winglets are already standard on aircraft. However, they are not biomimetic products. Biomimetic multi-winglets are in the numerical simulation and concept validation stage [15]. Humpback whale tubercles have application explorations on wind turbines and unmanned aerial vehicles [3]. However, commercial aircraft have not adopted them. The boxfish remains at the concept car stage. It has not been mass-produced [8]. Dragonfly corrugated vortex generators are mainly tried in laboratories and a few race cars.

6. Supporting Technologies and Tools

Biomimetic aerodynamic design needs support from three types of technical tools. These tools are performance prediction and shape optimization (CFD), complex structure manufacturing (additive manufacturing and other advanced manufacturing technologies), and design space exploration (machine learning and generative design).

6.1. Computational fluid dynamics (CFD)

CFD solves the core problems of performance prediction and parameter optimization. It evaluates the aerodynamic effect of biomimetic structures before making physical models. It also screens optimal parameters. For humpback whale tubercles, CFD is used to study vortex structure evolution at different angles of attack and Reynolds numbers [3]. For dragonfly corrugated airfoils, three-dimensional CFD simulations reveal the formation mechanism of leading-edge vortices and spanwise flow. For shark skin riblets, large eddy simulation is used to analyze the relationship between near-wall vortex structures and drag reduction. The value of CFD is greatly shortening

DOI: 10.54254/2753-8818/2026.37895

design cycles. It also reduces experimental costs. However, its accuracy depends on turbulence model selection and mesh quality. For biomimetic problems involving complex separated flows, CFD results still need wind tunnel validation [12].

6.2. Advanced manufacturing technologies

The manufacturability of biomimetic structures involves multiple technical paths. For micron-scale riblet structures, thin film bonding, imprinting, and laser processing can be used [10]. For complex biomimetic curved surfaces and three-dimensional structures, additive manufacturing (3D printing) provides an important supplement. It builds materials layer by layer. This can create complex geometries that traditional processes cannot easily achieve. Some studies have used additive manufacturing to make biomimetic multi-feather wingtip devices. They conducted wind tunnel experiments for characterization [15]. Riblet microstructures can also be manufactured by thin film, imprinting, and laser processing. Additive manufacturing is an important manufacturing tool for complex biomimetic structures. However, it is not the only method.

6.3. Machine learning and generative design

Machine learning applications in biomimetic aerodynamic design have gradually increased in recent years. However, the overall field is still in an exploratory stage. In surrogate models, researchers have begun to explore Gaussian Process Regression and neural networks. These build fast prediction models for aerodynamic performance. They replace high-cost CFD simulations [12]. In geometric parameter optimization, deep learning has been used to learn the mapping between geometric parameters and aerodynamic performance from CFD data [12]. Generative design goes further. Given performance targets and constraints, algorithms automatically generate geometric forms that meet the requirements [12].

It should be noted that these methods are still mainly in concept validation and preliminary exploration in biomimetic design. They are still far from mature engineering application. In particular, the scheme of "AI automatically discovering structures from biological databases" is more of a future vision at present. Existing research mostly focuses on specific geometric parameter optimization. It is not autonomous biomimetic shape discovery. The discussion of related content in this paper is expressed as a potential direction. It is not a mature method.

7. Conclusion

This paper presents a comprehensive review of biomimetic applications in the aerodynamic shape design of aviation and automobiles. The main line is how bio-inspired shapes and surfaces improve aerodynamic performance. This paper reviews typical biological models in two fields. These models include humpback whale leading-edge tubercles, shark skin riblets, boxfish body shape, dragonfly wing corrugations, and bird wingtip feathers. It also conducts a conditional cross-domain comparison.

The main findings can be summarized in four points.

First, biomimetics does provide valuable innovative ideas for aerodynamic shape design. Humpback whale tubercles can delay the stall angle by about 40% in scaled model experiments. Shark skin riblets achieve about 6% friction drag reduction on the A320 in real-aircraft validation. The boxfish provided shape inspiration for the Mercedes concept car. The full-scale vehicle Cd is 0.19. These data show that biomimetic design is indeed effective under specific conditions.

DOI: 10.54254/2753-8818/2026.37895

However, it must be emphasized that these data come from different experimental systems and test conditions. They should not be directly compared horizontally.

Second, the effectiveness of biomimetic design is highly dependent on operating conditions. Changes in Reynolds number, angle of attack, scale, and flow direction can weaken or even eliminate benefits. Humpback whale tubercles show no obvious benefit at low angles of attack. Riblets may increase drag when the flow yaw angle increases. Boxfish Cd values range from 0.06 to 0.24 in different studies. This shows that the same biological model can produce completely different results under different experimental conditions. Directly extending results from specific experimental conditions to general engineering rules is a tendency that biomimetic research must guard against.

Third, aviation and automobiles differ in Reynolds number, drag source, target operating conditions, and manufacturing constraints. This leads to different effects and feasibility for the same biomimetic structure in the two fields. Riblets have a relatively clear friction drag reduction effect on large commercial aircraft. This is because friction drag proportion is relatively large. The flow direction is also relatively stable. Their effect on passenger cars is relatively limited. This is because pressure drag dominates. The flow direction is also variable. However, this judgment should be regarded as an observation based on specific typical scenarios. It is not a universal rule for all aircraft or all vehicles.

Fourth, there is a huge gap from biological inspiration to engineering biomimetics to mass production application. The process goes from laboratory validation to scaled model testing to full-scale prototype to mass production product. Each stage may eliminate many seemingly promising schemes. Manufacturing difficulty, cost, durability, and operating condition adaptability are all real obstacles. Currently, biomimetic aerodynamic technologies that truly achieve large-scale engineering application are still limited. Riblets are one of the few success cases.

Recommendations for future research. Future biomimetic aerodynamic design should pay more attention to the following points. Clearly label the data source type. This includes biological model experiment, scaled model, CFD, wind tunnel experiment, and real vehicle test. Also label the specific indicator meaning. This includes friction drag or total drag. This avoids horizontal comparison of data under different conditions. Systematically evaluate the applicable conditions and failure conditions of biomimetic structures. Distinguish single-study observations from cross-study consensus. Do not only report positive performance. Move from form mimicry to mechanism mimicry. Understand the fluid dynamics principle behind the effectiveness of biological structures. Then transplant the principle, not the form, into engineering. Integrate aerodynamic performance with manufacturing feasibility, cost, and durability into a unified multidisciplinary optimization framework. Establish unified benchmark test cases and scaling similarity criteria in the field. This improves the comparability and repeatability of research results.

Biomimetics has opened a new window for aerodynamic shape design. However, whether the view from the window can truly land as engineering reality still requires more rigorous condition assessment. It also requires more systematic cross-domain comparison. It requires more practical engineering thinking.

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