

Application of Bionics in Wing Design of Aerospace Vehicles

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Abstract. With the rapid development of aviation technology, the requirements for aircraft performance are getting higher and higher, and traditional aircraft design is facing numerous challenges. Bionics provides new ideas and solutions for the development of aviation technology by imitating the structural and functional principles of natural organisms. In this paper, the limitations of traditional aircraft wings are first analyzed and the ideas of bionics in improving wing design are discussed. Then, it discusses the research progress in morphology bionics, structure bionics, function enhancement, and material innovation. The potential of bionics to improve the performance of aircraft, reduce energy consumption, and enhance stability is demonstrated. Through the integrated application of morpho-bionics, structural bionics and functional bionics, researchers have not only solved the shortcomings of conventional wings but also significantly improved the aerodynamic performance and flight efficiency of aircraft. This paper aims to provide useful references and inspirations to promote the innovation and development of aeronautics technology.

Keywords: Wing design; Structural bionics; Morphological bionics; Aerospace vehicles.

1. Introduction

The term bionics was first coined by J.E. Steele in the late 1950s. Bionics scholars' endeavor to develop new machines and technologies, or to solve mechanical technological problems, by understanding the structural and functional principles of living things. From this coined word, bionics, it can be seen that it is a cross-discipline consisting mainly of "biology" and "electronics".

The significance of bionics is that people can draw inspiration from the natural world, which has been iterating for 3.5 billion years, to solve real-world problems. Bionics allows research to minimize the need for extensive experimentation to obtain data and instead enables the extraction of naturally evolved more perfect data or models from existing biological ones and their application to machinery and new technologies. For example, Haiyue Yu's team summarized and analyzed the inspiration of plant leaves for materials and bionic structures [1]. The paper analyzed bionic structures and summarized research on material design in terms of photosynthesis structure, stress resistance structure, and auxiliary function structure.

In the field of aircraft design, bionics is more widely used. Aircraft can be divided into two main categories: lighter-than-air aircraft and heavier-than-air aircraft, of which the latter can be further subdivided into fixed-wing aircraft, rotary-wing aircraft, flapping-wing aircraft, and tilt-rotor aircraft. As can be seen from Fig. 1, regardless of the category of aircraft, their wings, cockpits, fuselages, and other hydrodynamics-related form designs have similarities to many living things in the natural world, such as insects and birds. People learn from their biological principles to fly in the blue sky. For example, Quoc-Viet Nguyen's team investigated a flapping wing aircraft that mimicked the wings of an insect [2]. As well as Di Tan's team also analyzed a variant form wing mimicking a raptor's spreading wing. All of them have injected new vitality into the research in the field of aviation [3].



(a) Ornithopter



(b) Tiltrotor

Fig. 1 Aircraft

This paper will first introduce the traditional aircraft wing defects and bionics improvement ideas. Then, it will explore the application of bionics in the design of aircraft wings, and analyze its research progress in morphology bionics, structure bionics, function enhancement and material innovation. At the same time, this paper will also pay attention to the challenges faced in this field and look forward to the prospects of the application of bionics in the design of aviation aircraft, aiming to provide useful references and inspiration for promoting the innovation and development of aviation technology.

2. Defects of traditional aircraft wings and ideas for bionics improvements

In the past two centuries since the birth of aircraft, the traditional wing, as the cornerstone of aviation technology, has undoubtedly played a pivotal role in promoting the development of flight technology. However, its inherent limitations have become increasingly prominent, as shown in Table 1. Fixed shapes and angles limit the optimization of flight performance, inefficient lift-to-drag ratios increase fuel consumption and lack adaptability to complex environments and changing missions.

Table 1. Fixed Wing defects

Defects	Details
Fixedness	The shape and angle of traditional wings are fixed and cannot be adjusted according to changes in flight conditions, which limits the optimization of flight performance.
Inefficient lift-to-drag ratio	In different flight phases (such as takeoff, cruising and landing), fixed wing designs may not provide the best lift-to-drag ratio, resulting in increased fuel consumption.
Poor adaptability	Facing different flight environments and meteorological conditions, traditional wings have limited adaptability, which may lead to poor control performance and affect flight safety.
Heavyweight	Due to the need to withstand different loads and maintain structural strength, traditional wings often require more materials, thereby increasing the overall weight of the aircraft.
Lack of flexibility	For flight missions that require rapid maneuvers or multi-purpose (such as military or special flights), fixed wings have limited flexibility and may not meet complex flight needs.
Aging and maintenance issues	Once fatigue or damage occurs to the fixed wing structure, it is often difficult to effectively repair it, increasing maintenance costs and risks.

These problems have led the research community to explore new solutions. Among them, deformable wings, as an exemplary application of bionics, are leading the way in revolutionizing aviation technology. Deformable wings are inspired by the flexibility of the wings of birds and insects in nature, which can flexibly adjust the wing shape according to flight requirements to achieve optimal

flight conditions. The advantages of deformable wings are shown in Table 2. These wings are not only able to adjust their shape in real-time according to changes in flight speed, altitude, and load to optimize aerodynamic efficiency, reduce drag, and increase lift, which improves fuel efficiency while significantly enhancing the handling and stability of the aircraft. This adaptive design allows the aircraft to maintain optimal performance during takeoff, cruise and landing, providing passengers with a more comfortable ride and pilots with a higher level of safety. More importantly, the introduction of deformable wing technology greatly expands the mission adaptability of the aircraft. Whether it is a military reconnaissance aircraft that requires a high degree of stealth, a fighter aircraft that pursues extreme maneuverability, or a drone that performs special tasks, the deformable wing enables the same platform to easily respond to diverse mission requirements. This demonstrates its broad application prospects in both military and civilian fields.

Table 2. Advantages of deformable wings

Advantages	Details
Improve aerodynamic efficiency	Deformable wings can adjust their shape according to flight conditions (such as speed, altitude and load), thereby optimizing aerodynamic characteristics, reducing drag and increasing lift. This helps improve fuel efficiency and reduce operating costs.
Enhance flight performance	By changing the shape of the wing, the aircraft can achieve better controllability and stability in different flight phases (such as takeoff, cruising, landing, etc.), and improve flight safety and comfort.
Expand mission capabilities	Deformable wings can enable the same platform to adapt to multiple mission requirements and are suitable for different types of flight missions, such as the stealth performance of military aircraft and the rapid maneuverability of fighter jets.
Coping with environmental changes	When facing different meteorological conditions and environmental factors (such as wind speed, airflow, etc.), deformable wings can be adjusted in real-time, which helps to improve the adaptability and safety of flight.
Promote technological innovation	Research on the technology of deformable wings often promotes technological progress in fields such as material science, control engineering and structural design, and promotes the development of the entire aviation industry.

3. Application of bionics in wing shape and structure design

3.1. Morphological bionics: imitating natural organisms to optimize wing shape

Morpho-bionics is an important branch of bionics in aeronautical wing design, which is dedicated to mimicking the morphological features of living organisms in nature to optimize the aerodynamic performance and flight efficiency of the wing. In morpho-bionic design, scientists study the wing morphology of birds, insects and other flying organisms, and through careful observation and analysis of their structure, shape, area distribution, and movement, extract the features that are beneficial to flight and apply them to the design of the wing.

For example, the wings of birds can adjust their morphology according to different flight phases and speeds during flight, and this flexibility is crucial for increasing lift, reducing drag and enhancing maneuverability. Therefore, morpho-bionic designers try to optimize aerodynamic performance by introducing design elements such as variable tips, swept-back angle adjustment mechanisms or flexible skins into the wings, so that the wings can change their shape according to the flight conditions just like a bird's wing.

Pan's team investigated the foldable bionic wings with beetles as the target, which provides a more comprehensive description of the bionic machinery research process [4]. The article first introduced the research material - seven-star ladybug beetle, and the methods used - ANSYS parameter setting

and FLUENT parameter setting. Then the structure of the ladybug hindwing and its data lead to the design of the bionic wing. As can be seen from the data in Tables 3 and 4, the data for the bionic wing is that of the ladybug wing data adjusted and scaled up isometrically. The data in this paper suggests that each set of bionic flapping wings would have to generate at least 2.5 kg of thrust to achieve a takeoff weight of 10 kg, especially with a wingspan of about 600 mm, which, if achieved, appears to exceed the thrust capacity of natural birds and raptors. Such a highly efficient wingspan would challenge our understanding of the aerodynamics and biomechanics observed in nature. However, there are still trade-offs to be made between the power source, the aerodynamic efficiency of the wing design, and the weighting in terms of material weight and durability.

Table 3. Ladybug related parameters

	Hind wing length (mm)	Hind wing width (mm)	Hind wing area (mm ²)
1	9.62	2.79	21.49
2	10.22	2.93	23.87
3	9.93	2.88	22.96
4	9.76	2.86	22.65
5	9.74	2.83	22.24
Average	9.85	2.85	22.62

Table 4. Parameters of bionic wings

Parameters	Value
Hind wing length (mm)	163
Hind wing width (mm)	48
Hind wing thickness (mm)	3.2
Hind wing area (mm ²)	6158
Pterygoid vein diameter (mm)	4

In addition, morpho-bionics also focuses on the overall layout and shape optimization of the wing. Simulating the streamlined shape and wing design of living organisms in nature, can effectively reduce air resistance during flight, increase the lift coefficient, and improve the stability and maneuverability of the wing. These designs not only help to enhance the flight performance of the aircraft but also reduce fuel consumption and noise pollution to a certain extent, realizing a more environmentally friendly and efficient flight.

3.2. Structural bionics: learning from biological structures to improve wing performance

Structural biomimicry explores the unique mechanical properties and optimization principles from the internal structure of living organisms and applies them to the structural design of airfoils. Through billions of years of evolution, living organisms in nature have developed many efficient, lightweight and durable structural forms, which are of great significance in improving the performance of airfoils. For example, the skeletal structure of birds has a very high strength to stiffness weight ratio, which reduces overall weight while ensuring structural stability. This structural feature provides useful insights for the lightweight design of airfoils. By borrowing the structural principles of the bird skeleton, designers can adopt new material technologies such as advanced composite materials and

porous structures to reduce the weight of the wing and improve the structural load-bearing capacity. Sandu Constantin's team has proposed a composite bionic technology designed to create extremely light and strong carbon fiber epoxy composite parts for aerospace components [5]. By utilizing a design that mimics the skeletal structure of a bird, this technique can significantly reduce the average density of an aerospace component, thereby improving the performance and efficiency of turbofans and other propulsion systems. With the introduction of internal support structures, the technology effectively reduces bending stresses and increases stiffness in components, giving it the potential for significant applications in the aerospace industry in the future.

In addition, insect wing structures exhibit unique mechanical properties. Their wings often consist of multilayered thin films that are extremely flexible and fatigue resistant. This structural feature provides new ideas for the durability design of wings. By mimicking the layered structure of insect wings, designers can develop a more durable and easy-to-maintain form of wing structure, thereby improving the reliability and service life of aircraft. However, as Chunxiang Pan's team mentioned in their research on beetles, how to balance the high efficiency of the power source, the aerodynamic efficiency of the wing design and the relationship between material lightness and durability in actual production is still a critical issue that needs to be resolved today.

3.3. Analysis of the comprehensive effect of morphological and structural bionics

In aviation wing design, the integrated application of morpho-bionics and structural bionics is not an isolated technical tool, but rather complementary and mutually reinforcing. When these two bionic design concepts are skillfully integrated, they can produce significant synergistic effects to further enhance the overall performance of the wing.

First, the comprehensive application of morphology and structure bionics can significantly optimize the aerodynamic performance of the wing. By mimicking the morphology of natural organisms, such as the wing shape of birds and the wing structure of insects, designers can create a more aerodynamic wing shape. At the same time, by combining the optimization principles of the internal structure of living organisms, the use of lightweight and high-strength materials and advanced structural forms such as porous and laminar can further reduce the weight of the wing and improve the structural load-bearing capacity. This dual optimization of form and structure allows the wing to more effectively utilize airflow during flight, reducing drag and increasing lift, thus significantly improving the aircraft's flight efficiency and fuel economy. For example, Mingyang Huang in his article took an eagle as an example, in order to investigate the optimization of kinematics of a multi-rod flapping wing configuration [6]. He simulated the eagle's wing motion, divided the inner and outer wings into three parts, namely, fluttering, folding, torsion degrees of freedom and structural flexibility, and optimized the design of the double-crank-rocker flutter wing configuration. Based on the optimization results, he fabricated a bionic eagle model with a wingspan of 1.5 m and conducted flight tests. The obtained research data showed that kinematics optimization can be achieved by using a multi-rod flapping wing configuration. The lift generated by the inner wing and the thrust generated by the outer wing are both increased. Thus, the correctness of the optimization results is verified.

Secondly, the integrated application of morphological and structural bionics can also enhance the adaptability and flexibility of the wing. Due to the fixed shape and structure of traditional wings, it is often difficult to adapt to the complex and changing flight environment and mission requirements. As one of the important achievements of morpho-bionics, deformable wings are able to adjust their shape and angle in real-time according to changes in flight conditions, thus optimizing aerodynamic performance. When this deformable technology is combined with structural bionics, the adaptability and flexibility of the wing can be further enhanced. For example, through the use of smart materials and advanced control algorithms, intelligent adjustment of the shape and structure of the wing can be realized so that it can maintain its optimal performance state in different flight stages and environments.

In addition, the integrated application of morphological and structural bionics also helps to enhance the durability and reliability of the wing. By mimicking the fatigue resistance and self-repairing ability of living organisms, designers can develop wing structures that are more durable and easier to maintain. Such structures are not only able to withstand greater loads and harsher environmental conditions but are also able to self-heal and extend their service life to a certain extent. It is important for improving aircraft reliability and reducing maintenance costs.

4. Application of bionics in improving wing function

4.1. Functional bionics: enhance the intelligence and maneuverability of wings

With the development of intelligent technology, it has become a trend to integrate intelligent elements into wing design. By mimicking the perception, decision-making and execution capabilities of living organisms, wings can be endowed with higher intelligence and maneuverability. Integrating sensors and perception systems on the wing enables it to monitor the flight environment and its state in real-time. By collecting and analyzing this data, the wing can autonomously adjust its flight attitude and speed to adapt to different flight conditions. Bionic control algorithms applicable to the wing are developed by drawing on the control mechanisms of living organisms. These algorithms can simulate the decision-making process of living organisms, enabling the wing to make optimal flight decisions in complex environments, and improving maneuverability and safety.

Zhu Lianqing's team has mentioned the rapid advancement of intelligent materials and structures, as well as innovative sensing and control technologies [7]. This series of technological innovations not only promoted the in-depth research and development of smart skin materials but also facilitated the refinement of flexible deformation mechanism design. At the same time, breakthroughs in distributed drive control and flexible sensing technologies have given strong impetus to the field. These comprehensive achievements have greatly accelerated the research and development of the new adaptive deformation wing technology, making the deformation wing with excellent flexible deformation capability, intelligent sensing and precise control characteristics gradually move from theoretical conception to practical application.

4.2. Biomimetic materials: improving wing performance and durability

In the field of aerospace, the application of biomimetic materials has revolutionized the improvement of wing performance and durability. By mimicking the structure and properties of living organisms in nature, these materials not only enhance the mechanical properties of the wing but also extend its service life and reduce maintenance costs.

Jiyu Sun's team had designed a biomimetic aerospace material based on the microstructure of beetle sheath wings [8]. Since almost all adult insects can fly, their sheaths must have low mass and high efficiency, which requires fine and complex micro/nanostructures to realize. These structures provide useful templates for the biomimetic design of new advanced composites. Sun's team implemented this idea to design biomimetic aerospace materials in this study. They proposed a bionic column and laminate (BCL) model for aircraft skins. Equal Quality (EQ) and Equal Thickness (ET) models were developed for comparative study. The coupled mechanical, heat transfer and thermal structure analysis and optimized design of these models were performed using ANSYS Workbench to determine the optimized parameters for material design. The research results will guide the development of advanced bionic composite aerospace materials.

5. Summary

Bionics is widely used in wing design and has made significant contributions to the field of aviation in terms of bionic morphology, bionic structure and bionic materials. Through in-depth research and imitation of natural biological forms, structures, functions and materials, researchers have not only solved many defects of traditional wings, but also significantly improved the aerodynamic

performance, flight efficiency, adaptability and flexibility of aircraft. The comprehensive application of morphology bionics, structure bionics and function bionics demonstrate the great potential of bionics in promoting the innovation and development of aviation technology. At the same time, the further development and application of bionics still face many challenges. How to balance the high efficiency of the power source, the aerodynamic efficiency of the wing design, and the relationship between the lightweight and durability of the materials are the key issues that need to be solved urgently. In addition, as a cross-discipline, the breakthrough of bionics cannot be separated from the continuous development and support of materials science, dynamics, fluid mechanics and other related fields.

References

- [1] Hanyue Yu, et al. Bionic structures and materials inspired by plant leaves: A comprehensive review for innovative problem-solving. *Progress in Materials Science*, 2023, 139: 101181
- [2] Nguyen Q V, Chan W L, Debiasi M. Hybrid design and performance tests of a hovering insect-inspired flapping-wing micro aerial vehicle. *Journal of Bionic Engineering*, 2016, 13(2): 235-248.
- [3] Tang D, Huang X, Che J, et al. Quantitative analysis of the morphing wing mechanism of raptors: Analysis methods, folding motions, and bionic design of Falco Peregrinus. *Fundamental Research*, 2022.
- [4] Chunxiang Pan, et al. Research on bionic foldable spray aircraft wings. *Journal of Engineering Research*. Available online 20 May 2024.
- [5] Sandu C, Vintila S, Sima M, et al. A bionic technology for aerospace components made of carbon fiber epoxy composites. *AIP Conference Proceedings*, 2018, 22(1).
- [6] Huang M. Optimization of flapping wing mechanism of bionic eagle. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2019, 233(9): 3260-3272.
- [7] Sun J, Liu C, Du H, et al. Design of a bionic aviation material based on the microstructure of beetle's elytra. *International Journal of Heat and Mass Transfer*, 2017, 114: 62-72.
- [8] Lianqing Z H U, Guangkai S U N, Hong L I. Application and development of intelligent flexible deformation wing technology. *Journal of Mechanical Engineering*, 2018, 54(13): 28-42.