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The Development and Prospect of Micro Air Vehicles

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Abstract: This paper systematically reviews the evolution of Micro Air Vehicle (MAV) aerofoil design, covering the geometric optimization and development from fixed-wing, rotary-wing, and flapping-wing to biomimetic-wing designs. In low Reynolds number environments, there are four main types of fixed-wing aerofoils, considered the classic designs for MAVs and have significantly contributed to the future development of MAV aerofoils. Rotary-wing and flapping-wing MAVs represent the initial application of bionics in aerofoil design. At the same time, the lift mechanisms discovered in insects and birds have since officially introduced MAV aerofoil design into the field of biomimetics. By integrating the locomotion mechanisms of animals such as stingrays and beetles, current research on biomimetic aerofoils has developed deployable and multi-parameter morphing wings Meanwhile, through the fusion of new and traditional technologies, the lift-to-drag ratio and flight efficiency are significantly improved. Finally, the paper summarizes the research methods and future directions of MAV aerofoil design, pointing out that the aerodynamic principles at low Reynolds numbers and the bionic kinematic principles of animals are the current research bottlenecks. These challenges can be addressed through cross-disciplinary research and further experimental validation to optimize MAV aerofoil designs.

Keywords: Micro Air Vehicle, Fixed-wing aerofoil, Biomimetic aerofoil, Lift mechanism

1. Introduction

Micro Air Vehicles (MAVs) are small, lightweight Unmanned Aerial Vehicles (UAVs). Typically, their wingspans are less than 15 cm (approximately 6 inches), and they operate at flight speeds ranging from 5 ms^{-1} to 23 ms^{-1} [1]. Due to their compact size and lightweight structure, MAVs can be deployed in complex scenarios that are beyond the reach of conventional methods. They can carry sensors to collect data in areas that are difficult for standard approaches to access. In military operations, MAVs are often used for battlefield reconnaissance, target tracking, and other high-risk missions. Their small size allows them to evade enemy radar detection and provide critical real-time intelligence. In civilian applications, MAVs can be equipped with high-resolution cameras to conduct urban patrols or border surveillance, ensuring the security of key infrastructure. In environmental monitoring, MAVs are capable of real-time monitoring of natural disasters and climate change, providing crucial data for emergency response efforts. A typical MAV operates at altitudes below 300 meters, with a flight endurance ranging from 5 to 30 minutes and a mission radius of approximately 10 kilometres [2].

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Compared to traditional aircraft, MAVs face unique design challenges. Firstly, due to the shorter chord lengths and lower speeds of MAVs, their flight Reynolds numbers are significantly lower than those of conventional aircraft. While the Reynolds number of commercial aircraft is around 107, the Reynolds number of MAVs is only in the range of 104 to 105 [3]. At low Reynolds numbers, the characteristics of airflow differ considerably, with the turbulence layer separating earlier, which greatly reduces flight efficiency. This also negatively affects their controllability [4]. In low Reynolds number conditions, airflow is often dominated by viscous fluid behaviours [4], making the well-studied aerodynamic mechanisms of high Reynolds number aircraft not fully applicable.

The aerofoil is the heart of an aircraft. This is because the aerofoil influences an aircraft's cruise speed, take-off and landing performance, stall speed, controllability (especially near-stall conditions), and aerodynamic efficiency during all phases of flight [5]. The significant difference in flight environments has rendered the well-developed thick aerofoils ineffective in this new domain, necessitating the development of new aerofoils specifically tailored to the low Reynolds number conditions. Therefore, research into optimizing the geometric design of MAV aerofoils has become particularly critical.

Furthermore, low Reynolds number flight conditions place higher demands on factors such as surface smoothness, curvature distribution, and thickness design of aerofoils. In recent years, many studies have focused on optimizing the geometric shapes of MAV aerofoils to maintain favourable aerodynamic performance under low Reynolds number conditions. These studies encompass various aspects, including comparisons of fixed-wing aerofoil geometries, aerofoil cross-section designs, and the recent rise of biomimetic aerofoils.

In the exploration of new aerofoil designs, biomimetics has gradually become an attractive direction. Biomimetics draws inspiration from nature, applying the motion and structural characteristics of animals to the design. Researchers have created more complex and efficient aerofoils. They can sustain better aerodynamic performance in low Reynolds number conditions [6]. In recent years, research on biomimetic aerofoils has entered the realm of multidisciplinary studies. The rise of computational fluid dynamics (CFD), combined with emerging technologies such as smart materials and flexible structures, has opened up promising prospects for the development of new biomimetic wings for MAVs.

By reviewing the development of MAV aerofoil geometries and providing an outlook on future directions, this study aims to offer a theoretical foundation for future designs and inspire further innovations. Additionally, it seeks to offer new insights for the continued optimization of MAV aerofoils under the interdisciplinary research of biomimetics, materials science, and CFD.

2. MAV Aerofoil Overview

Table 1: The features and applications of different aerofoils.

Wing Shape	Characteristics	Difficulties to be solved	Applications
Fixed Wing	Better payloads Endurance capabilities High forward speed	Separation phenomenon Limited manoeuvrability	Environmental monitoring Remote sensing
Rotary Wing	Low forward speed Vertical take-off/landing Suitable in urban places	Flight deficiency Dynamic Control Dynamic Drag Issues	Urban reconnaissance Search and rescue Observation
Flapping Wing	High manoeuvrability Ability to hover Stealthiness	Complicated Kinematic Principles of Flapping	Indoor reconnaissance Search and rescue Observation

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The overall design of MAVs is purpose-driven [6]. The aircraft requires different flight paths and attitudes from take-off to landing during various mission phases. Due to the diversity of mission requirements, researchers have developed a variety of aerofoil shapes and structures to optimise MAV performance across different flight modes.

MAV aerofoil designs can be broadly classified into three categories: fixed-wing, rotary-wing, and flapping-wing [7]. Table 1 outlines the characteristics of these three aerofoil types and their applications.

2.1. Fixed-wing Aerofoil

The fixed-wing design is one of the earliest MAV aerofoil designs, inspired by traditional aircraft concepts. It features a relatively simple structure and stable flight performance. Fixed-wing MAVs are typically suited for long-duration missions, offering higher payload capacity and longer endurance. However, the fixed-wing design also faces several complex airflow challenges, such as the separation phenomenon, extra drag caused by tip vortices, and rolling instabilities [7]. To generate greater lift, fixed-wing MAVs must operate at higher forward speeds compared to other MAV wing types. The formula for calculating lift is shown below in equation (1):

$$L = \frac{1}{2}\rho V^2 S C_L \tag{1}$$

Where L is the lift force, ρ is the air density, V is the velocity of the aircraft relative to their, S is the area of the aerofoil and C_L is the lift coefficient.

The increase in relative airspeed limits the flexibility and manoeuvrability of fixed-wing MAVs. Unlike other wing types, they cannot perform complex operations such as hovering, or they risk stalling. These limitations in application scenarios have accelerated the development of other MAV wing designs.

2.2. Rotary-wing Aerofoil

The rotary-wing design introduces a structure similar to that of helicopters, giving MAVs the ability to perform vertical take-off, landing, and hovering. Rotary-wing MAVs do not require runways or additional space for take-off and landing, making them more flexible for operations in confined or urban environments. Additionally, the rotary structure allows MAVs to hover at low speeds, enabling tasks such as urban surveillance, search and rescue, and indoor operations. However, despite the high flexibility of rotary-wing MAVs, they have lower flight efficiency, higher energy consumption, and greater mechanical complexity, requiring more maintenance and precise control [7].

2.3. Flapping-wing Aerofoil

Flapping-wing Micro Air Vehicles (FWMAVs) generate lift and thrust through wing flapping, enabling them to perform complex manoeuvres such as hovering, low-speed flight, and rapid turns. Current FWMAV research is divided into two biologically inspired modes: insect-inspired and bird-inspired [8]. Compared to fixed-wing and rotary-wing MAVs, FWMAVs have unique advantages, including high manoeuvrability, low noise, and strong stealth capabilities, making them highly promising for missions like reconnaissance and post-disaster search and rescue.

3. The Development of Fixed-wing Aerofoils

The discussion of fixed-wing aerofoil design is divided into two perspectives: top view and side view. From the top view, the four most common wing designs are the Rectangular Wing, Zimmerman Wing, Inverse Zimmerman Wing, and Elliptical Wing. From the side view, the geometric shapes of these

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wings are typically fitted using 3rd-order polynomials. The four unique aerofoils are depicted below, with Figure 1 being the Rectangular Wing, figure 2 being the Zimmerman Wing, figure 3 being the Inverse Zimmerman Wing and Figure 4 being the Elliptical Wing.

In the study by N. I. Ismail et al., CFD simulations were conducted on four wing types under the same side view conditions (using the same 3rd-order polynomial expression) [9]. They focused on analysing differences in lift coefficient, drag coefficient, and the lift-to-drag ratio, which represents aerodynamic efficiency. The results showed that the Elliptical Wing had slightly better aerodynamic performance compared to the other wing types. It demonstrated vantages in stall Ange of attack AoA_{stall} and maximum lift coefficient $C_{L_{max}}$, with $C_{L_{max}}$ being at least 4.33% higher than the other wing types, and the minimum drag coefficient $C_{D_{min}}$ being at least 8.45% lower. The Inverse Zimmerman Wing exhibited a slower increase in drag coefficient C_D and showed better stability due to a larger slope of pitching moment coefficient C_M. In terms of C_M, the Inverse Zimmerman Wing outperformed the other wing types by 17.39%. The Zimmerman Wing showed the best aerodynamic efficiency, with a lift-to-drag ratio of 6.80, which was 1.35% higher than the other wing types. These three wing types each demonstrated advantages in specific areas. Therefore, the corresponding wing type should be prioritized based on the intended application of the MAV. However, researchers generally agree that the Zimmerman Wing is the most superior fixed-wing design, and this consensus has been widely accepted.

From the side view perspective, using a 3rd-order polynomial for fitting has also seemingly become a consensus. Researchers have used these fitted aerofoil shapes to build models and obtained many favourable results. In further studies, N. I. Ismail quantitatively compared the performance of three aerofoil shapes fitted using 3rd-order polynomials [10]. The detailed parameters of the three aerofoils are listed in Table 2 below.

The study pointed out that Profile 3 had a significant advantage of around 20% in lift coefficient, but its drag coefficient C_D was at least 57.5% higher than the other aerofoils. However, the large slope of the pitching moment coefficient C_M for Profile 3 indicated better stability. Although this research only compared the advantages and disadvantages of three different aerofoil profiles fitted with 3rd-order polynomials, it did not provide general conclusions or patterns about polynomial fitting. Therefore, further investigation is needed.

Nevertheless, due to the aerodynamic complexity at low Reynolds numbers, the shortcomings of fixed-wing aerofoils in terms of stability and efficiency remain unresolved [4]. This has prompted scientists and engineers to explore new design concepts that can better adapt to MAV flight conditions.

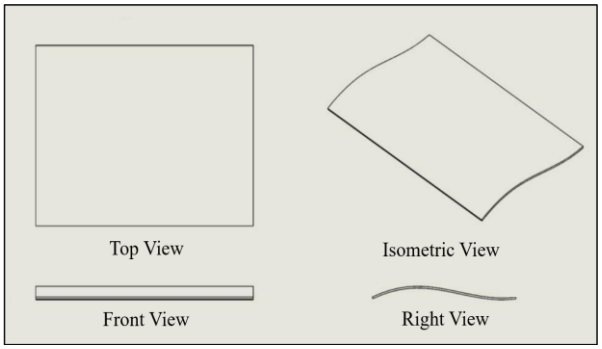


Figure 1: Rectangular Wing.

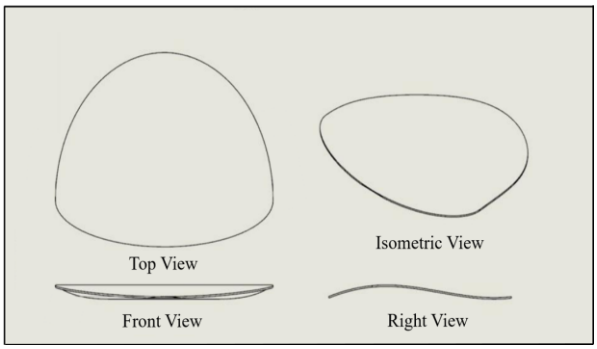


Figure 2: Zimmerman Wing.

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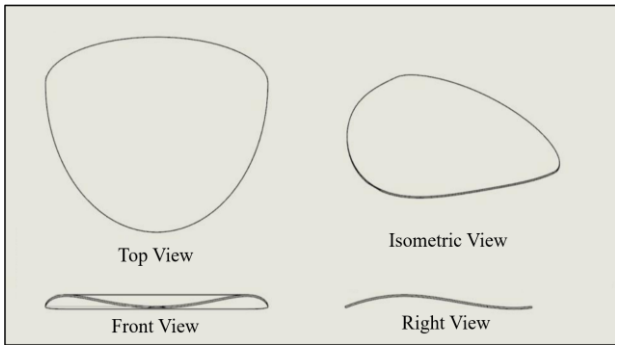


Figure 3: Inverse Zimmerman Wing.

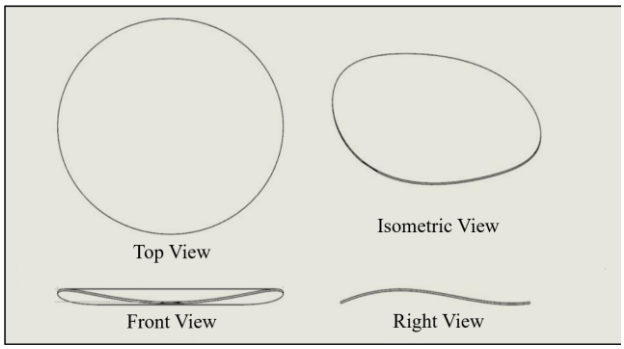


Figure 4: Elliptical Wing.

Table 2: The detailed parameters of three aerofoils.

Aerofoil	Profile 1	Profile 2	Profile 3
Equation	$y = 0.0703x^3 - 0.1266x^2 + 0.0563x - 2 \times 10^{-16}$	$y = 0.1405x^3 - 0.2531x^2 + 0.1126x - 5 \times 10^{-16}$	$y = 0.281x^3 - 0.5062x^2 + 0.2252x + 9 \times 10^{-16}$
Chord Length (mm)	150	150	150
Wing Area (mm^2)	35640	35254	36610
Reynolds Number	100 000	100 000	100 000
Velocity (ms^{-1})	10.074	10.074	10.074
Aspect Ratio	0.6313	0.6382	0.6146
Camber Percentage	3.8%	7.5%	15.0%

4. The Development of Biomimetic-wing Aerofoils

Today, MAVs are expected to perform more complex tasks. For example, a specific mission might require an MAV to change altitude periodically during its flight to the mission area, hover to collect data upon arrival, and then return to its starting point after completing the task [11]. Figure 5 is the route of a multi-stage MAV mission. This demands that the MAV can change speed rapidly and adjust its flight attitude. Those are what fixed-wing MAVs designed for single flight modes cannot do. As a result, researchers have turned their attention to biomimetics, combining it with MAV aerofoil design to seek breakthroughs.

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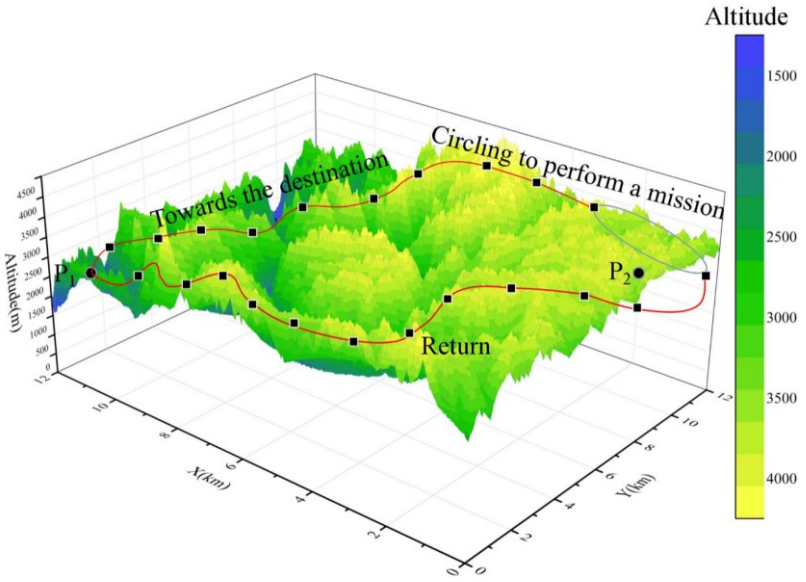


Figure 5: The complex route of an MAV in a certain mission.

Earlier in the research on flapping wings, researchers introduced biomimetic methods, and today's biomimetic wings are an extension of flapping wings. Flapping-wing designs typically mimic the flapping actions of insects and birds, with the flapping mechanism imitating the high-frequency beats of insect flight, making it suitable for hovering and short-distance missions. In contrast, biomimetic wing designs draw inspiration from a wider range of biological movements. Those movements include flapping, wing deformation etc. This more refined application of biomimetics has led to innovations such as flexible wings and morphing wings, enabling MAVs to make small wing adjustments during flight to adapt to different airflow conditions and mission requirements. These advancements can be applied to more complex tasks, such as variable-speed flight and environmental adaptation.

Biomimetics has greatly advanced the research on MAV aerofoil design. Researchers have not only delved deeper into the flight characteristics of animals in nature but also expanded the range of species being mimicked. These now include not just insects and birds but also flying mammals like bats and even designs inspired by the movements of stingrays as they glide through water [11]. This section will discuss the development of biomimetic wings from the perspectives of lift mechanisms and current research.

4.1. Lift Mechanisms

Researchers have uncovered several key mechanisms involved in insect and bird flapping flight, such as the clap-fling mechanism, delayed stall, rotational effect, and wake capture [8]. These effects are not independent. They occur simultaneously during flapping, increasing lift collectively.

The clap-fling mechanism is observed during the rapid wingbeats of insects. A cycle consists of the wings moving up and down, with the end of the cycle defined as the completion of the upward stroke. Weis Fogh's research on wasps showed that at the end of each stroke cycle, the insect's wings overlap at the back [12]. At the start of the next cycle, the wings quickly open, creating a low-pressure region between them, which increases lift at the beginning of the new wingbeat cycle. Theoretical calculations and experiments by Maxworthy et al. also confirmed the validity of this mechanism [13].

The delayed stall mechanism, also known as delayed shedding, refers to the formation of a vortex at the leading edge of the wing during the stroke, which remains attached to the wing surface for an extended time, significantly increasing the lift coefficient. Ellington's study on moths revealed that

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leading-edge vortices generated during the downstroke produce higher lift [14]. Sun Mao and colleagues further validated this mechanism using CFD [15].

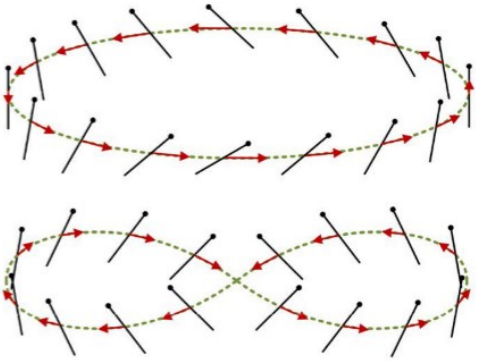


Figure 6: The wingtip paths of a flapping hummingbird.

The rotational effect occurs when the wings rotate during the flapping motion. Dickinson et al. studied the flight of fruit flies (Drosophila) and described the complete process of the rotational effect [16]. After a stroke, the wing rapidly rotates, altering the angle of attack. This change in angle causes different airflow velocities on the upper and lower wing surfaces, creating a large pressure difference that enhances lift.

Wake capture happens during the transition between the downstroke and the upstroke. Due to the high frequency of wingbeats, the wings encounter airflow from the opposite direction of the previous cycle, increasing the relative speed between the wings and air, and providing additional lift.

Researchers have also observed and summarized the wingtip motion trajectories of insects and birds during hovering, noting that their wingtip paths resemble a figure-eight or figure-zero shape, as shown in Figure 6 below [17]. The flapping plane is nearly horizontal, revealing the mechanics behind the hovering flight.

4.2. Relative Research

To advance the development of biomimetic wings for MAVs, researchers have selectively integrated past research findings and introduced innovations based on them. This section will introduce several recent studies on biomimetic MAV wings, then analyse how they incorporated previous research and highlight their innovations.

In the study by S. Huang et al. [11], the researchers observed that the shape changes of stingrays during movement could alter their speed and improve their efficiency. They also drew on existing research on the fixed-wing aerofoil S5010. Based on this, they applied algebraic deformation to the side profile of the original aerofoil, creating a new design whose shape is shown in Figure 7. By introducing multiple small adjustments (multi-parameter variations) shown in Figure 8, they optimized the lift, drag, and pitching moment coefficients of the new aerofoil. Compared to the original design, they found that the lift coefficient of the multi-parameter morphing aerofoil shifted from negative to positive at a 0° angle of attack. At a 2° angle of attack, the lift coefficient growth rate reached its peak, increasing by 47.27%, and the lift-to-drag ratio improved by 50.00%.

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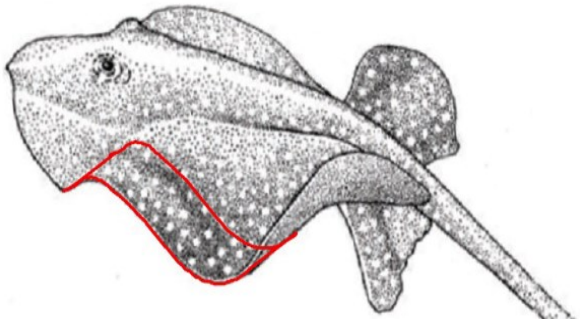


Figure 7: Shape of the stingray-inspired aerofoil.

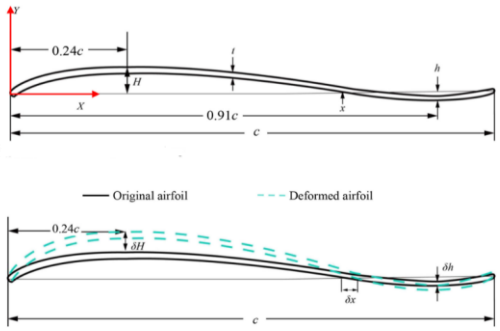


Figure 8: The aerofoil and its deformation.

J. Sun et al. drew inspiration from the hind wings of Protaetia breviaries (a type of beetle) for their research on foldable wings [18]. They developed a bionic deployable wing (BD-W) model based on the folding mechanism and elliptical wing vein structure of the beetle's hind wings. Using CFD simulations and small wind tunnel tests, they analysed how parameters such as wind speed, flapping frequency, and angle of attack affected the aerodynamic characteristics of the wing. In their design shown in Figure 9, high-performance nylon was used for the wing veins, while polyethene terephthalate (PETP) film was used as the membrane covering the wing. This combination demonstrated sufficient strength, flexibility, and durability under high-frequency wing flapping. By optimizing the parameters, they achieved the best aerodynamic efficiency at a freestream velocity of 3 ms^{-1}, a flapping frequency of 10 Hz, and an angle of attack of 15°, with a lift-to-drag ratio of 4.91.

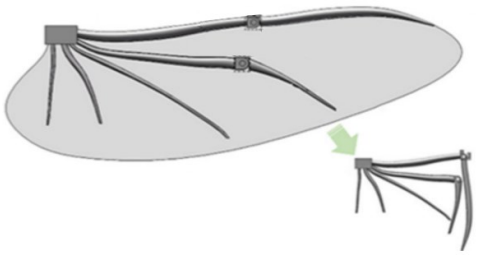


Figure 9: The BD-W is inspired by beetles' hind wings.

Table 3 presents an analysis of several current studies, highlighting how they have integrated previous research findings. It also reveals the directions that are likely to bring breakthroughs to biomimetic wing designs. In section 5, a summary and outlook on the development of MAV aerofoils will be provided [11, 18, 19].

Table 3: Summary of some biomimetic wing designs.

Researchers	Inspiration	Based on	Progressive Aspects
S. Huang et al (2021)	Stingray	Data of previous fixed-wing aerofoil	Dynamic morphing
S. Suhaimi et al (2021)	Bat	Wind tunnel experiments	Wind tunnel validations
J. Sun et al (2024)	Beetle	Wind tunnel experiments	Advanced materials Wind tunnel validations

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5. The Prospect of Aerofoil Designs

5.1. The Overall Prospect

The summary in Table 3 reflects the current design patterns of MAV aerofoils: building upon previous research while integrating the latest technologies. Biomimetic aerofoils have now become a key focus of research. Often, by studying the movement patterns of a specific animal, researchers can develop a relatively mature aerofoil design. The common approach involves analysing the kinematic mechanisms of the animal's movement first, then using CFD simulations, followed by creating a real-world model for testing and finally comparing the experimental results with the simulation data. This has become the standard practice among researchers.

5.2. The Future Prospect

Despite significant breakthroughs in recent years, there are still many unresolved issues in the field of MAV research.

One of the key challenges in MAV development is addressing the aerodynamic problems at low Reynolds numbers. Some progress has been made. Researchers have optimized aerofoils that performed well in experiments through CFD simulations and wind tunnel tests. They reduced flow separation and improved the lift-to-drag ratio at low Reynolds numbers. Additionally, the introduction of biomimetic designs and flexible materials has enhanced the stability and efficiency of MAVs during low-speed flight. However, some problems remain unsolved, particularly in effectively controlling boundary layer instability and vortex formation at low Reynolds numbers. These issues limit the application of MAVs in complex environments.

There is also room for further exploration of biomimetic kinematic principles. For example, insect flapping mechanisms involve highly complex unsteady aerodynamic phenomena, which are more difficult to predict than the fluid dynamics of fixed-wing or rotary-wing flight. Although fluid dynamics simulations and experimental validation have revealed some fundamental principles, most of the research remains in the qualitative analysis stage, and precise mathematical models to fully explain the complex airflow interactions during flapping are still lacking [8]. Moreover, the three-dimensional motion trajectories of insect and bird wings, flexible deformations, and the coordination of their musculoskeletal systems make it even more challenging to accurately simulate and replicate biological flight.

Furthermore, current research often focuses on a specific aerofoil inspired by a particular animal, but few studies compare the performance of different biomimetic aerofoils derived from various animals [6]. By comparing biomimetic aerofoils, researchers could identify the optimal design that integrates the latest findings. Additionally, some studies rely solely on CFD simulations, lacking wind tunnel experimental data for validation. Real-world wind tunnel tests could help verify simulation results and provide insights for further aerofoil optimization.

6. Conclusion

Due to its unique application scenarios and performance characteristics, research on MAVs has become an important branch of aviation technology. The development of MAV aerofoils has evolved from the early optimization of fixed-wing designs to the current exploration of biomimetic aerofoils. There are four main types of fixed-wing aerofoils, including Rectangular Wing, Zimmerman Wing, Inverse Zimmerman Wing and Elliptical Wing. It is a widely acknowledged consensus that Zimmerman Wing has the best aerodynamic performance, even though each wing has its advantages and limitations, tailored to different scenarios. Their side profiles are often fitted using 3rd-order polynomials. Then, biomimetic aerofoil research has been initiated. Researchers have gradually

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gained insight into the lift mechanisms of certain animals, yielding many promising results. These lift mechanisms include the clap-fling mechanism, the delayed stall mechanism, the rotational effect and the wake capture. By combining previous research findings with emerging computational and material technologies, researchers have developed numerous biomimetic aerofoils with great potential. Various MAV aerofoils capable of conducting specific movements during flights have been made.

However, there are still many research bottlenecks that need to be overcome in MAV aerofoil design. Aerodynamic problems at low Reynolds numbers are among them. Further research is needed to enhance flight performance while maintaining flight efficiency, probably through aerofoil refinements and the unravelment of the low Reynolds number environment properties. Meanwhile, apart from the four biomimetic kinematic principles introduced, other detailed lift mechanisms of the relevant animals remain unknown. It is advisable to dive deeper into the field of kinematic movements itself and draw further conclusions. Last but not least, efforts shall be made to link the current biomimetic results. Finally, more wind tunnel experiments shall be conducted in reality to testify to the results of the CFD simulation.

In the future, MAV flight performance is expected to improve further, enabling the execution of more complex flight missions.

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