Progress and Prospects on Design of UAV Wing Shapes

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Abstract. Driven by the growing demand in various industrial sectors, emerging unmanned aerial vehicles (UAVs) are becoming increasingly diverse. The development of fixed-wing UAVs is also accelerating. The correct selection of wings is crucial for improving the performance of UAVs (including lift, drag, stability, and maneuverability). However, the selection of UAV airfoils is mostly based on the experience of predecessors or continuous trial and error, which consumes a lot of time and cost. Therefore, this article conducts an in-depth study of commonly used airfoils in fixed-wing UAVs, starting from symmetrical, asymmetrical (convex), flat-bottom, laminar flow, and high-lift airfoils. Each airfoil form and their respective advantages and disadvantages are discussed separately. Further, the practical application evidence of various airfoils is analyzed. This study provides a comprehensive classification designed to help designers optimize airfoil selection, save time and resources, and reduce costs associated with traditional trial-and-error methods. In conclusion, this work is of great value in helping UAV designers improve the efficiency of airfoil selection and optimization design.

Keywords: Airfoil, UAVs, Aerodynamic performance

1 Introduction

With the development of society, drones have been involved in all walks of life. As the demand for the use of drones in various industries continues to increase, the emergence of diversified configurations of drones, the proposal of distinctive design concepts, and the improvement of safe and stable use requirements have promoted drone designers to continue to innovate and effectively Targeted development of advanced and efficient drones with industry characteristics [1]. Among them, the choice of an airfoil is crucial to the performance of the drone, because it directly affects the lift, drag, stability, and maneuverability of the drone. Different airfoils can provide different performance characteristics under specific flight conditions. For example, certain airfoil designs help produce greater lift at low speeds, making them suitable for drones that need to hover in the air for long periods or perform precise operations at low speeds. Other airfoils can provide better high-speed performance and lower drag, suitable for drones that need to move quickly or fly long distances. In addition, the choice of airfoil can affect the take-off and landing performance of the drone, as well as its stability under severe weather conditions [2, 3]. Therefore,

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according to the specific application goals and flight environment of the UAV, careful selection and optimization of the airfoil are key steps to ensure that the UAV achieves the expected flight performance and efficiency.

However, when selecting airfoils for fixed-wing UAVs, the selection is generally based on experience. However, as simulations and experiments progress, new airfoils are constantly selected and improved, thus wasting a lot of time and resources. Insufficient knowledge of the airfoil's characteristics is obtained during this process, further increasing costs. Therefore, this article summarizes and classifies the airfoils currently commonly used for fixed-wing UAVs, and lists the characteristics of different airfoils to help researchers save time and costs.

2 Lift Mechanism and Design Principles of UAV Wings

2.1 Wing Aerodynamic Analysis

The lift generated by a fixed-wing drone is mainly due to the interaction between its airfoil design and the surrounding air. As shown in Figure 1, when a fixed-wing drone moves forward, the specially designed shape of the airfoil causes the air flowing above the wing to move faster than the air flowing below. According to Bernoulli's principle, faster fluid has lower pressure, so the pressure above the airfoil is lower than the pressure below the airfoil, creating upward lift. In addition, the interaction between the airfoil and the air also follows Newton's third law, that is, every action force has an equal reaction force. The drone wings push the air downward, and the air pushes the airfoil upward with equal force, further increasing lift [4-6].

The lift force formula is [7]:

$$Y = \frac{1}{2} \cdot C_y \cdot \rho \cdot V^2 \cdot S\#(1)$$

where ρ refers to the atmospheric density at an altitude above sea level, V denotes the drone flight speed, C_y denotes the lift coefficient, S denotes the Plane shape (projected) area of the wing.

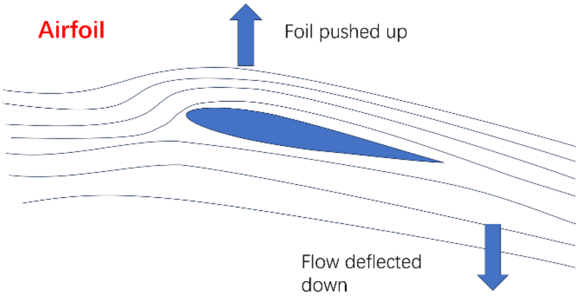

Fig. 1. Lift principal diagram. (Photo/Picture credit : Original)

2.2 Design Principles and Shape Characteristics of UAV Wings

The design principles of fixed-wing UAV wings are to ensure optimal aerodynamic performance, structural strength, stability, and controllability, as well as the ability to adapt to specific mission requirements. Aerodynamic efficiency requires a design that optimizes the ratio of lift to drag to increase the range and endurance of the drone. Structural strength ensures that the wings can withstand stress and vibration during flight, while stability and controllability ensure that the drone can operate reliably under various flight conditions. In addition, the wing design also needs to consider the specific use of the UAV, such as reconnaissance, cargo transportation, or operation in a specific environment, to adapt to different flight missions and environmental conditions [8].

The size parameters of UAV fixed wings are also important in wing selection. Airfoil shape, wingspan, chord length, thickness, twist, and angle of attack have a direct impact on flight performance. The airfoil determines the basic characteristics of lift and drag. Symmetrical airfoils are suitable for high-speed flight, while convex airfoils produce more lift at low speeds. Wingspan affects lift-to-drag ratio and maneuverability, and a longer wingspan is suitable for long-distance flight. Chord length and thickness affect wing area and structural strength, which in turn affects lift and drag. Adjustment of twist and angle of attack is used to control lift distribution and flight attitude. Optimizing these parameters can improve flight efficiency and stability. By carefully designing these parameters, the drone can be provided with optimal flight performance and adaptability [9].

In this research, several commonly used UAV airfoils and their different advantages, disadvantages, and usage scenarios are summarized for better selection and understanding of wings.

3 Advances and Applications of Different Airfoils

3.1 Symmetric Airfoil

Symmetric airfoil, as the name suggests, means that the upper and lower surfaces of the airfoil have the same shape, such as airfoils National Advisory Committee for Aeronautics (NACA) 0012 and NACA 0009 Airfoils, etc. As shown in Figure 2, the maximum thickness of NACA0012 is 12% of the chord length [10]. This thickness is distributed symmetrically on the upper and lower surfaces of the airfoil. NACA 0012 performs similarly at positive and negative angles of attack. This design allows the airfoil to generate no lift at no angle of attack. This feature is particularly important for drones that require high maneuverability and high-speed flight performance.

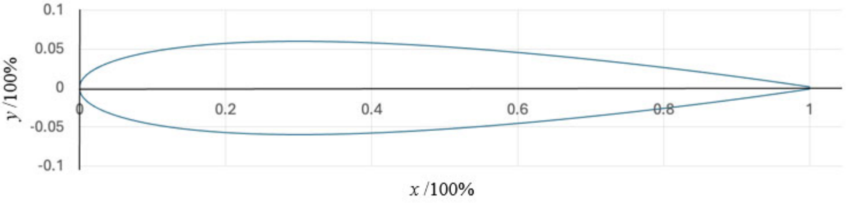

Fig. 2. NACA 0012 airfoils coordinates [11].

The main advantage of a symmetrical airfoil is that it provides good aerodynamic performance, especially in aerobatics and high-speed flight. This airfoil can maintain low drag over a wide range of angles of attack while providing stable lift, which is crucial for drones that perform complex maneuvers and precise control. In addition, due to the symmetry of its structure, the symmetrical airfoil allows the drone to maintain good flight performance when flying upside down (i.e., flying upside down), which is useful in stunt performances and certain competition scenarios.

In aerodynamic research and experiments, symmetrical airfoils such as NACA 0012 are also often used as benchmark airfoils to evaluate and compare the performance of other airfoil designs. Its stable performance and predictable behavior make it ideal for wind tunnel experiments and computational fluid dynamics simulations.

3.2 Asymmetric (Convex) Airfoil

An asymmetric (convex) airfoil is an airfoil with different shapes on the upper and lower surfaces, usually with the upper surface being more curved than the lower surface. This design causes the air flowing over the upper surface of the airfoil to move faster than the air flowing over the lower surface, which, according to Bernoulli's principle, creates lower pressure above the airfoil, creating lift. Asymmetric airfoils are particularly suitable for aircraft flying at low speeds because they can generate greater lift at lower speeds. This feature is especially important for aircraft requiring short take-off and landing (STOL) capabilities.

Another key feature of the asymmetric airfoil is that it can provide a better lift-to-drag ratio, which can greatly improve flight efficiency and reduce energy consumption. This type of airfoil commonly finds applications in commercial aircraft, UAVs, and light aircraft such as the NACA 4 Series airfoil, Clark Y airfoil, Eppler airfoil, Selig airfoil, and SD7037 airfoil. UAVs equipped with this type of airfoil usually have high requirements for takeoff and landing performance, as well as stability and controllability during low-speed flight.

Taking the NACA 2412 airfoil [12] which is shown in Figure 3 as an example, the maximum thickness position of the NACA2412 airfoil is located at 24% of the chord, and the magnitude of the symmetrical bend line is 12. Since the maximum thickness is not 50%, this airfoil is called an asymmetric airfoil. As shown in Figure 3, the upper surface of the wing is more curved than the lower surface, which is more conducive to generating more lift at lower speeds.

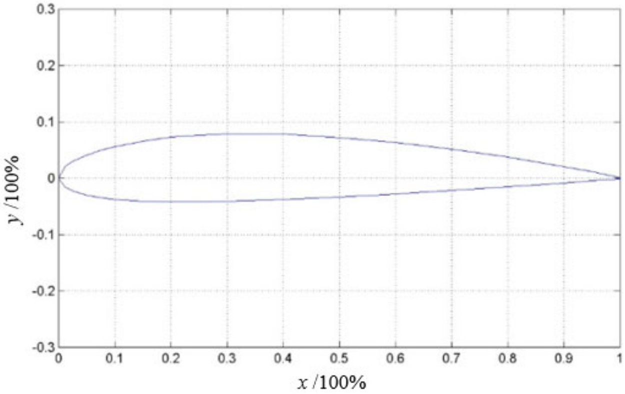

Fig. 3. NACA-2401 airfoil coordinates [13].

When designing an asymmetric airfoil, the maximum thickness, maximum convex position of the airfoil, and the leading and trailing edge shapes of the airfoil are important considerations, which are related to the optimization of flight performance and specific flight mission requirements. By adjusting these parameters, the lift and drag characteristics of the airfoil under different flight conditions can be controlled, thereby achieving precise control of the overall performance of the aircraft.

3.3 Flat Bottom Airfoil

Flat Bottom Airfoil is a special airfoil design characterized by the fact that the lower surface of the airfoil is almost straight, while the upper surface shows a significant curve. This design is relatively simple and common in aviation.

Flat-bottomed airfoils can generate greater lift at lower flight speeds, making them ideal for aircraft such as light aircraft and drones that require STOL capabilities. This airfoil exhibits good lift characteristics when flying at low speeds but may produce greater drag when flying at high speeds. At the same time, this airfoil is usually easier to predict in terms of stall angle, which is beneficial to flight safety and pilot training. However, pilots need to be aware that flat-bottomed airfoils may suddenly lose lift as they approach stall speed [14].

Flat-bottomed airfoils are relatively simple in structure and less expensive to manufacture, making them particularly popular in small aircraft and educational model aircraft. Flat-bottom airfoils are widely used in education, entertainment, and certain types of commercial drones. For example, the NACA 4412 airfoil shown in Figure 4 is a typical example of a flat-bottom airfoil, with its good performance and lift characteristics in low-speed flight conditions. It is very suitable for aircraft that require precise control at low speeds or take off and land in limited spaces, such as agricultural spraying drones, environmental monitoring fixed-wing drones, and remote-control aircraft for beginners. The flat-bottom airfoil is an ideal choice.

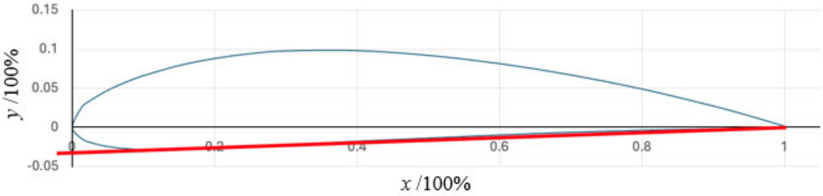

Fig. 4. NACA 4412 airfoil coordinates (data from Airfoil Tools [11]).

In general, flat-bottomed airfoils have found a niche in certain aviation applications due to their excellent lift characteristics at low speeds, ease of manufacturing, and novice-friendly flight performance. However, designers need to consider the specific needs of the aircraft and expected flight performance when selecting an airfoil.

3.4 Laminar Airfoil

Laminar airfoils are designed to maintain a laminar boundary layer over the longest possible distance over the airfoil surface. Compared with traditional turbulent airfoils, laminar airfoils can significantly reduce frictional drag, thereby improving aircraft performance. This type of airfoil is particularly important in the aviation and aerospace fields, especially when designing high-performance aircraft and drones.

Laminar airfoils have their special shape design. They usually have a smoother and specific shape. As shown in Figure 5, laminar airfoils generally have a thin leading edge and a moderate maximum thickness position to promote laminar flow. development and maintenance. Unlike other airfoils, the performance of laminar airfoils strongly depends on the Reynolds number. According to the research of Hu and Yang [15], many high-speed aircraft with laminar flow airfoils have been born in the past 40 years, but their performance at high chord Reynolds numbers is stronger than that at low Reynolds numbers. Within a specific Reynolds number range, laminar airfoils can exhibit their best performance.

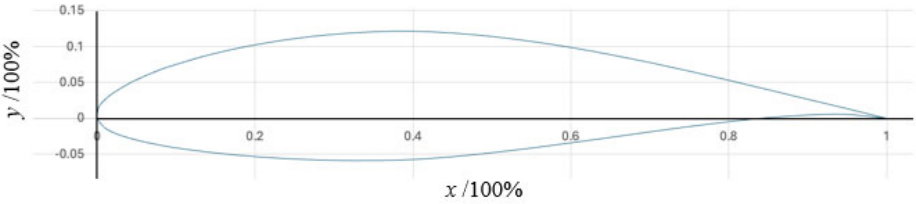

Fig. 5. NACA 64(3)-618 airfoil coordinates which data from Airfoil Tools [11].

Laminar flow airfoils can significantly reduce frictional drag by maintaining a laminar flow state on the airfoil surface. This is because the airflow in laminar flow is smoother than in turbulent flow, thereby reducing energy loss. But this also results in the high sensitivity of laminar airfoils, because laminar flow is more susceptible to surface roughness than turbulent flow, pollution irregular shape, and other factors. Therefore, laminar flow airfoils have high requirements for maintaining clean and smooth surfaces.

Common laminar flow airfoils include NACA 643-618, NACA 65(2)-415, and NACA 66(2)-215, etc. UAVs using this airfoil include senseFly eBee X, RQ-4 Global Hawk, and some drones. Human-robot racing league racing machine.

3.5 High Lift Airfoil

A high-lift airfoil is a specially designed airfoil designed to produce maximum lift under low-speed flight conditions, especially for aircraft requiring STOL capabilities. As shown in Figure 6, the design features of high-lift airfoils include increased camber, which makes the upper surface of the airfoil more curved, thereby increasing the difference in airflow velocity at low speeds and increasing lift. At the same time, high-lift airfoils are usually thicker [16], which not only provides more space for internal structures but also helps improve lift characteristics, allowing the aircraft to maintain flight at lower speeds. In addition, this airfoil is often equipped with lift-enhancing devices such as flaps and slats [17], which are deployed during takeoff and landing to significantly add additional lift and retract to reduce drag when not needed.

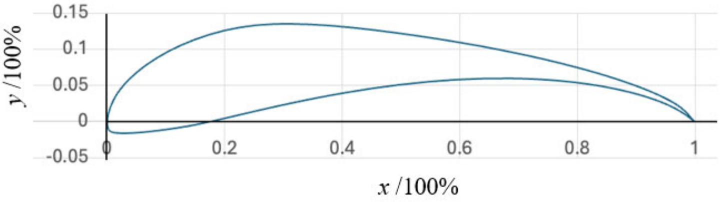

Fig. 6. Selig 1223 airfoil coordinates with data from Airfoil Tools [11].

The high-lift airfoil also specifically optimizes the low-speed stall characteristics. By controlling the separation of airflow on the airfoil, the occurrence of stall is delayed, which is crucial to maintaining stability and safety during low-speed flight. This airfoil design provides flexibility in adjusting the angle of attack, allowing pilots to operate over a wide range of angles of attack, especially during takeoff and landing. In addition, when designing a high-lift airfoil, structural strength, weight, and aerodynamic performance need to be considered comprehensively to ensure that the airfoil is not only aerodynamically effective but also structurally reliable and economical. Through these integrated design features and technologies, high-lift airfoils become the key to providing excellent performance under specific flight conditions, especially in applications requiring STOL capabilities.

3.6 Discussion

Above all, the characteristics, advantages, and disadvantages representative airfoils of different airfoils were summarized in Table 1:

Table 1. Comparative overview of different airfoil types: characteristics, advantages, Disadvantages, and examples

Airfoil Type	Shape Characteristics	Advantages	Disadvantages	Representative Airfoils
Symmetric	Upper and lower	Good	Lower lift,	NACA 0012

	surfaces have the same shape	maneuverability, suitable for high-speed and aerobatic flight	higher takeoff and landing speeds	
Asymmetric	Upper surface has a greater curvature than the lower surface	Generates more lift, suitable for low-speed flight	Prone to stall at high angles of attack	NACA 2412
Flat-Bottom	The bottom surface is nearly flat	Simple structure, easy to manufacture	High drag, not suitable for high-speed flight	Clark Y
Laminar Flow	Smooth surface with gradually changing thickness	Low drag, high efficiency	High manufacturing requirements, sensitive to surface smoothness	NACA 643-618, NACA 65(2)-415
High Lift	Large thickness and curvature may include flaps and other devices	Generates high lift, suitable for STOL	High drag, not suitable for high-speed flight	NACA 230 series

This table provides a basic overview to understand the basic characteristics of different airfoils and their application scenarios. It is important to note that representative airfoils are only examples among many designs, and airfoil selection and optimization should consider specific flight missions and performance requirements. For example, Global Hawk, Pterosaur and WJ-600A/D drones are all fixed-wing reconnaissance drones, but their usage scenarios are very different. Global Hawk [18] is mainly used to provide global surveillance and reconnaissance capabilities. Considering its long-endurance and high-efficiency requirements, the Global Hawk is likely to use an efficient laminar flow airfoil or a specially optimized long-endurance airfoil. Such an airfoil helps reduce drag during flight and improves fuel efficiency, thereby achieving long-term flight endurance. The wing shape of the Pterosaur UAV ensures that the Pterosaur UAV can provide good lift and flight stability when flying at medium and low speeds, making it suitable for performing complex ground surveillance tasks. WJ-600A/D is an unmanned combat aircraft designed to perform high-speed, multi-mission tasks [19]. Its airfoil design is likely to be specially selected to optimize high-speed flight performance. It may use an airfoil that can reduce drag and improve aerodynamic efficiency during high-speed flight, such as some improved laminar flow airfoil or a symmetrical airfoil suitable for high-speed operation.

4 Conclusion

This article explains the importance of wing selection in improving UAV performance for a variety of applications. Symmetrical airfoils are essential for high-speed, agile drones due to their uniform shape, while asymmetrical and flat-bottom airfoils are indispensable for drones that require high lift at low speeds and short take-off and landing capabilities. Laminar flow airfoils emerged as a solution to minimize drag and maximize efficiency and are particularly valuable for high-performance and long-range drones. High-lift airfoils have greater camber and thickness, which is particularly beneficial for UAVs operating in short takeoff and landing environments. This review not only illustrates basic aerodynamic analysis and design principles but also outlines the evolution and applications of different airfoil types. This article can serve as a foundational guide for drone designers, saving time and cost on design selections that are consistent with the drone's intended use case and operating environment.

However, only 5 typical airfoils have been studied in this article. A wider range of airfoils has not yet been thoroughly explored. With scholars' in-depth research on airfoils, many airfoil characteristics have been integrated, not simply any of the above airfoils. Therefore, it is crucial to have a more detailed discussion and summary of the fused airfoil in future research.

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