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Review of the Impact of Uav Airfoil Design on Aerodynamic Performance

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ABSTRACT
This paper systematically reviews the core issues and latest research progress in the field of unmanned aerial vehicle (UAV) airfoil design. First, the unique low Reynolds number flight environment of UAVs and its challenges to the aerodynamic performance of airfoils are explained, and the formation mechanism and influence of key flow phenomena such as laminar separation bubbles (LSBs) are analyzed in detail. Subsequently, the computational fluid dynamics (CFD) method and wind tunnel experimental technology used for airfoil analysis are discussed in depth, and their advantages and limitations are compared. On this basis, the airfoil geometry parameterization method, various optimization algorithms (such as genetic algorithm, particle swarm optimization) and advanced optimization strategies such as multi-objective and multi-point design are systematically sorted out. Finally, the main challenges faced by current research are summarized, and future development directions such as intelligent airfoils and multidisciplinary design optimization are prospected, aiming to provide comprehensive theoretical reference and technical guidance for the research and development of airfoils for high-performance UAVs.

KEYWORDS
UAV; Airfoil design; Aerodynamic performance; Computational fluid dynamics

1 Introduction

1.1 Research Background and Significance

With the rapid development of technology, unmanned aerial vehicles (UAVs) have been widely used in military reconnaissance, civil aerial photography, agricultural plant protection, logistics and transportation, etc. [1]. Different mission scenarios have put forward increasingly stringent requirements on the endurance, payload, flight stability and maneuverability of UAVs. As the core aerodynamic component of an aircraft, the geometric shape of the airfoil directly determines the lift, drag and torque characteristics of the aircraft, and is the fundamental factor affecting the comprehensive flight performance of the UAV. Therefore, optimizing the airfoil design according to specific mission requirements is a key technical path to improve the capabilities of the UAV platform.

1.2 The Core Aerodynamic Challenge: Low Reynolds Number Flight

Unlike large manned aircraft that usually fly under high Reynolds number ($Re > 10^7$), the typical flight conditions of small and medium-sized UAVs usually correspond to the low Reynolds number ($Re \approx 10^4 \sim 10^6$) range [2]. In this Reynolds number range, the viscosity effect of air becomes particularly prominent, resulting in significant changes in the physical mechanism of the flow around the airfoil. The flow in the boundary layer is more likely to separate under adverse pressure gradients, and is often accompanied by complex phenomena such as the formation, transition and reattachment of laminar separation bubbles (LSBs). These unique flow characteristics pose a severe challenge to the aerodynamic performance of the airfoil, causing it to exhibit behavior that is completely different from that at high Reynolds numbers.

1.3 Overview of Current Research Status

Currently, the research on low Reynolds number UAV airfoils presents a situation of theoretical analysis, numerical simulation and experimental research. The research methodology has gradually evolved from the traditional airfoil library selection to the automated and refined design based on parametric modeling and advanced optimization algorithms. Computational fluid dynamics (CFD) technology, especially the Reynolds-averaged Navier-Stokes (RANS) method combined with the transition model, has become the mainstream tool for airfoil analysis and design [3]. At the same time, wind tunnel experiments are an indispensable means to obtain high-reliability data and verify numerical models, and their testing technology and data correction methods are also constantly developing.

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1.4 Objective and Structure of this Review

This review aims to systematically sort out and summarize the research results in the field of UAV airfoil design and its impact on aerodynamic performance in recent years. This paper will first deeply analyze the basic aerodynamic characteristics of the airfoil at low Reynolds numbers; secondly, it will introduce in detail the CFD method and wind tunnel experimental technology for airfoil performance analysis and evaluation; then, it will focus on the core technologies of airfoil optimization design, including parameterization methods, optimization algorithms and advanced strategies; finally, based on the summary of current research challenges, it will look forward to future development directions.

2 Fundamental Aerodynamics of Uav Airfoils at Low Reynolds Numbers

2.1 The Laminar Separation Bubble (LSB) Phenomenon

Laminar separation bubble is the most typical feature of low Reynolds number airfoil flow. Its formation mechanism is as follows: the laminar boundary layer on the suction surface of the airfoil leading edge undergoes flow separation under the action of the adverse pressure gradient. The free shear layer after separation undergoes transition driven by flow instability, becomes turbulent and reattaches to the airfoil, thereby forming a closed area containing a recirculation zone between the separation point and the reattachment point, namely LSB [2, 4]. According to its length and its impact on the external flow field, LSB can be divided into "short bubbles" and "long bubbles". Short bubbles are small in size and have limited impact on the airfoil pressure distribution; while long bubbles can cover a considerable area of the airfoil, significantly changing the effective airfoil shape and showing strong unsteadiness, which is the main reason for the deterioration of aerodynamic performance. The key factors affecting the formation of LSB include Reynolds number, angle of attack, airfoil geometry and incoming flow turbulence.

2.2 Impact of LSB on Aerodynamic Performance

The existence and evolution of LSB have a profound impact on the aerodynamic performance of low Reynolds number airfoils, which is mainly reflected in the following aspects:

Nonlinearity of lift characteristics: The position and size of LSB vary with the angle of attack, which may cause the lift coefficient to show nonlinear growth in the small angle of attack range, or even a sudden change in the slope of the lift curve. This "dead zone" phenomenon is extremely detrimental to the flight control and stability of UAVs [3].

Deterioration of drag characteristics: The formation of LSB significantly increases the pressure difference drag of the airfoil. Inside the separation bubble, due to the low flow rate and the pressure close to a constant, it is impossible to produce effective pressure recovery in the rear section like the attached flow, resulting in a sharp increase in total drag and a decrease in aerodynamic efficiency (lift-to-drag ratio) [5].

Change in stall characteristics: The rupture of LSB is one of the key causes of airfoil stall. As the angle of attack increases, the separation bubble may suddenly rupture, forming a large-scale separation starting from the leading edge, resulting in a sudden drop in lift and a sharp increase in drag, that is, leading edge stall. This makes the maximum lift coefficient of the airfoil much lower than that at high Reynolds numbers, and the stall process is more abrupt.

Hysteresis effect of aerodynamics: During the process of increasing or decreasing the angle of attack, the formation of LSB and the rupture path may be inconsistent, resulting in the formation of a "hysteresis loop" in the lift and drag coefficient curves. This unsteady effect will affect the dynamic response and handling quality of the UAV [6].

3 Analysis and Evaluation Methods for Airfoil Performance

3.1 Computational Fluid Dynamics (CFD) Methods

CFD technology simulates the flow around airfoils by numerically solving the governing equations of the fluid (such as the Reynolds-averaged Navier-Stokes, RANS equations) and is a core tool for modern airfoil design. To accurately predict complex flows at low Reynolds numbers, the key is to select an appropriate physical model. For example, transition models such as γ-$Re\theta t$ are widely used to couple to turbulence models such as k-ω SST to accurately capture the transition process of the boundary layer and the formation and evolution of LSB [3]. In terms of software tools, high-fidelity CFD software such as ANSYS Fluent and OpenFOAM provide comprehensive modeling capabilities, while engineering estimation programs such as XFOIL are still widely used in the preliminary design and optimization stages because they can quickly and accurately analyze LSB phenomena [4].

3.2 Wind Tunnel Testing and Experimental Validation

Wind tunnel experiments are the ultimate standard for obtaining airfoil aerodynamic performance data, revealing the physical mechanism of flow, and verifying the accuracy of CFD models [7]. The main experimental techniques include: force measurement tests that directly measure lift, drag, and torque coefficients using a balance; pressure measurement tests that arrange pressure holes on the wing surface to obtain detailed pressure distribution; and flow display technologies such as oil flow and particle image velocimetry (PIV) to visualize separation, transition, and LSB structures. However, wind tunnel experiments also face core challenges, such as the need to correct the interference of the tunnel wall effect on the flow field, and the experimental Reynolds number is often difficult to fully reproduce the actual flight Reynolds number, and data correction needs to be performed through extrapolation methods [8]. High-quality experimental data is a valuable benchmark for evaluating and improving CFD numerical models.

4 Airfoil Optimization Design: Algorithms and Strategies

4.1 Airfoil Geometric Parameterization Methods

The first step in airfoil optimization design is to parameterize its geometry. This involves using a limited set of design variables to accurately describe and control the airfoil profile. This allows the optimization algorithm to search within a defined design space. The table below compares several mainstream parameterization methods.

Table 1 shows that comparison of airfoil parameterization methods.

Table 1 Comparison of airfoil parameterization methods

	English Abbreviation	Main Features
Shape Classification Function Transformation	CST	Flexible control and good orthogonality make it suitable for describing a wide range of airfoil shapes.
Hicks-Henne function	H-H	Strong local correction capability, often used for fine-tuning a baseline airfoil.
PARSEC method	PARSEC	Parameters have clear geometric or aerodynamic meaning (such as leading edge radius) and are intuitive.
Bezier NURBS curve	Bézier/NURBS	General computer graphics method, generating smooth curves and intuitive control points.

4.2 Optimization Algorithms

After selecting the parameterization method, an optimization algorithm needs to be used to drive the iterative improvement of the airfoil shape. The gradient optimization algorithm converges quickly, but it is easy to fall into the local optimal solution. For complex multi-peak problems such as airfoil design, global optimization algorithms are more popular. Among them, the genetic algorithm (GA) and its multi-objective version (NSGA-II) have become one of the most widely used algorithms due to their strong robustness and independence from gradient information [3]. In addition, the particle swarm optimization (PSO) algorithm is also often used in airfoil optimization design due to its simple principle and relatively fast convergence speed [9].

4.3 Advanced Optimization Strategies

In order to cope with the time-consuming challenge of CFD evaluation and meet the requirements of multiple tasks, researchers have developed a variety of advanced optimization strategies. Surrogate-Assisted Optimization uses computationally inexpensive mathematical models (such as Kriging model and Gaussian process regression) to approximate high-fidelity CFD responses, thereby significantly improving optimization efficiency [10]. Multi-Objective & Multi-Point Design aims to balance different or even conflicting performance indicators (such as maximum lift and maximum lift-to-drag ratio), or to simultaneously take into account the performance requirements of drones in different flight phases such as cruising, climbing, take-off and landing. Recent studies have shown that by introducing tiny "geometric bumps" on the upper surface of the airfoil, the position and shape of the LSB can be effectively controlled, thereby suppressing the aerodynamic nonlinearity at small angles of attack. This is a successful case of optimizing low Reynolds number characteristics [3].

5 Challenges and Future Outlook

5.1 Current Research Challenges

Although drone airfoil design has made great progress, it still faces many challenges. At the physical model level, developing high-precision and high-universality transition and large-scale separation flow models remains a challenge in the CFD field. At the computational efficiency level, the computational cost of high-fidelity simulations (such as large eddy simulations) that include complex unsteady effects is still high, making it difficult to apply them on a large scale in engineering optimization. At the experimental verification level, there is still a lack of a systematic and comprehensive open experimental database of low-Reynolds number airfoils internationally, which limits the verification and validation of numerical methods. In addition, how to efficiently carry out multidisciplinary coupled design such as aerodynamics, structure, stealth, and acoustics is a key bottleneck in achieving the optimal overall performance of aircraft [11].

5.2 Future Development Directions

Looking into the future, UAV airfoil design is developing in a more intelligent, adaptive and comprehensive direction. The intelligent design method that integrates artificial intelligence and machine learning is expected to realize the automation and intelligence of the entire process from parameterization to performance evaluation of airfoils. Morphing Smart Airfoil technology, by actively changing the airfoil's curvature, thickness and other shapes, enables a single airfoil to adapt to different flight conditions, thereby breaking through the performance bottleneck of fixed airfoils. It is a revolutionary development direction in the future [12]. Multidisciplinary design optimization (MDO) integrates aerodynamic shape with other disciplines (such as structure, control, and stealth) into a unified framework for collaborative optimization, which is an inevitable trend to maximize the overall performance of aircraft. At the same time, with the improvement of computing power, high-fidelity methods such as large eddy simulation (LES) and direct numerical simulation (DNS) will play a more important role in mechanism research and key design point verification.

5.3 Conclusion

This paper reviews the current research on the impact of UAV airfoil design on aerodynamic performance. The core challenge is to effectively deal with the complex flow phenomena represented by laminar separation bubbles at low Reynolds numbers and the resulting deterioration of aerodynamic performance. Computational fluid dynamics and wind tunnel experiments, as complementary research methods, have jointly promoted the understanding of the physical mechanisms in this field. Parametric modeling, global optimization algorithms represented by genetic algorithms, and advanced strategies such as agent model assistance and multi-objective design together constitute the key technical path for the design of modern high-performance UAV airfoils. Future research will focus on developing more intelligent design methods, variant airfoil technologies that can actively adapt to flight conditions, and multidisciplinary design optimization to achieve optimal overall performance, providing continuous impetus for the research and development of the next generation of high-performance UAVs.

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