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Flow Separation Control and Aerodynamic Enhancement Mechanism of Bionic Micro-structured Airfoil at Low Reynolds Numbers

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Abstract. The airfoil is prone to flow separation under low Reynolds number flow conditions, which leads to a sharp deterioration of aerodynamic performance of micro aircraft. This paper proposes a bionic separation flow airfoil design concept, which turns to fix the separation point through the leading edge sharpening structure and induce stable vortices, combined with the rear edge arc airfoil surface to promote flow reattachment and vortex stability. Numerical simulation results show that This bionic airfoil can effectively suppress flow separation over a wide Angle of attack (8°-16°), significantly increase lift coefficient, significantly improve stall characteristics, and extend the efficient operating range by about twice compared to traditional airfoils. Parameter analysis reveals the influence of key geometric parameters such as the leading edge tip Angle and the installation position of the arc wing on aerodynamic performance.

Keywords: Low Reynolds number, flow separation control, Bionic airfoil, aerodynamic efficiency enhancement

1. Low Reynolds number flow characteristics and bionic airfoil design principles

1.1. The constraints of low Reynolds number on the aerodynamic performance of micro aircraft

The direct aerodynamic consequence of low Reynolds numbers is a decrease in lift coefficient and an increase in drag coefficient, resulting in a significant deterioration in lift-to-drag ratio. The airfoil may stall at medium angles of attack due to extensive flow separation and lose most of the lift. More importantly, the unsteady shedding of separation vortices can induce periodic or random asymmetric loads, causing pitch, roll oscillation of the airframe. It poses a serious challenge to flight attitude stability and control systems. Miniature aircraft, which are usually light in weight and small in inertia, are more sensitive to such unsteady aerodynamic forces and are prone to fall into continuous aeroelastic coupling vibrations, even leading to flight mission failure. How to effectively suppress or manage flow separation under low Reynolds number conditions [1], It becomes a core scientific issue for improving the aerodynamic performance and flight quality of micro aircraft.

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Traditional airfoil design theories, such as those based on potential flow theory or high Reynolds number optimization experience (like the NACA series of airfoils), often fail at low Reynolds number conditions. Such designs typically aim for higher lift and lower drag in attached flow conditions, and their aerodynamic characteristics rely heavily on laminar to turbulent transition and strong anti-separation ability of turbulent boundary layers. At low Reynolds numbers, the transition may be delayed or not occur at all, and the laminar boundary layer is prone to separation and cannot be reattached after separation. Simply optimizing the arc or thickness distribution in the airfoil is difficult to fundamentally change the nature of flow instability at low Reynolds numbers, and a shift from the traditional attachment flow design paradigm to a new design concept that can actively adapt to or utilize low Reynolds number separation flows is needed.

1.2. Inspiration from the wing configuration of flying animals in nature

One of the core aerodynamic functions of the leading edge structure of biological wings is to fix the flow separation point. For example, the comb-like structure at the leading edge of an owl wing is believed to induce stable vortices in advance during the descent, thereby maintaining lift over a wide range of angles of attack. In bionics studies, a similar mechanism is refined as the "fixed separation flow" or "leading edge vortex" stabilization concept, based on the principle that A well-designed raised or sharp leading edge structure can force the flow separation at a specific position and lock the separation point at that geometric feature [2], which does not move significantly with minor changes in the Angle of attack. The resulting separation shear layer rolls up to form a relatively stable concentrated vortex, which attaches above the wing surface and creates a sustained low-pressure area, thereby providing strong support to the wing surface. Provide an additional, stable lift contribution.

Inspired by the biological mechanism mentioned above, the design concept of the bionic separation flow airfoil emerged. The core of this concept is to abandon the pursuit of fully attached flow and instead actively design a controllable, stable leading edge separation vortex system. The specific design idea is: Introducing a definite geometric mutation (such as sharpening, steps, protrusions) at the leading edge of the airfoil artificially creates a fixed, advanced separation point, and then, through a specific geometric configuration at the rear of the airfoil (such as a large curvature, appropriate surface curvature), guides the separation shear layer downstream and attaches or stabilizes above the wing surface for as long as possible. To form a "separation bubble" or "attachment vortex," this design aims to transform the originally harmful, unsteady random separation into a beneficial, quasi-steady fixed vortex lift device, and the "leading edge sharp-flat plate + trailing edge arc-shaped wing" combination configuration proposed in this study is a concrete implementation of this design concept, aiming to verify the feasibility of the fixed separation vortex enhancement mechanism through geometric simplification.

2. Numerical simulation methods and verification of bionic separation flow airfoil shapes

2.1. Geometric model construction and computational setup

The combined bionic airfoil is constructed with a sharp leading edge thin plate at the front end and a continuous curvature arc wing surface at the rear end. The geometric parameters of the leading edge sharpened plate include the sharpening Angle and plate length. Its core function is to force the flow to undergo a fixed separation at the sharp leading edge, while the rear edge arc airfoil provides a smooth guiding surface for the separated shear layer flow through its continuous curvature variation.

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Intended to facilitate the stability of vortices and possible reattachment, the two parts are connected in a tangential or smooth transition manner to ensure geometric continuity. The chord length of the airfoil, the relative thickness (mainly determined by the rear arc), and the ratio of the lengths of the front and rear segments are key design variables for comparative analysis Conventional symmetrical airfoils or low Reynolds number reference airfoils with the same chord length and maximum thickness were also established as control models.

A C-shaped grid is adopted, with the inlet as the velocity inlet and the outlet as the pressure outlet. The wing surface is a non-slip wall. The calculation domain size is large enough to reduce the boundary effect. To study the aerodynamic characteristics at different angles of attack, the Angle of attack is changed by rotating the grid or changing the direction of the incoming flow. The simulation range covers from the small Angle of attack to the post-stall Angle of attack [3].

Mesh densification is carried out on the airfoil surface, particularly at the leading edge sharpening, near the connection points, and in the area with large arc curvature at the trailing edge to ensure sufficient mesh resolution within the boundary layer. The height of the first layer of mesh is calculated to ensure that the dimensionless wall distance $y^* \approx 1$ to meet the requirements of the selected turbulence model for near-wall processing, and the mesh type is a mixture of structural and unstructural meshes. The grid independence of the system was verified by using three sets of meshes of different densities, namely coarse, medium and fine, to calculate the drag coefficient under typical states (such as 0° and 10° angles of attack) for adaptability in the complex geometry area and for computational efficiency in the mainstream area. When a 50% increase in the number of meshes results in a lift coefficient change of less than 0.5% and a drag coefficient change of less than 1%, it is considered that the current mesh density meets the accuracy requirements, and this set of meshes is selected for all subsequent operating conditions.

2.2. Turbulence model selection and verification of calculation accuracy

The SST k-ω, Transition SST, and Spalart-Allmaras models were compared. The Transition SST, with its built-in transition prediction capability, is more suitable for simulating laminar separation and reattachment by comparing typical angle-of-attack flow field structures (such as separation bubble size, vortex center position) and aerodynamic coefficients (lift, The performance of each model was evaluated based on the prediction of drag. The preliminary analysis indicated that the Transition SST model was more consistent with the high-precision simulation or experimental phenomena in the relevant literature in capturing the evolution of the fixed separation vortices at the leading edge and their interaction with the rear wing surface, and this model was selected as the main computational model for this study.

To verify reliability, the classic airfoil (such as E387) was simulated, and the aerodynamic coefficients and pressure distribution were compared with the experimental data. The comparison results showed that within the target Reynolds number range, the stall characteristics predicted by the numerical simulation, the lift line slope, and the pressure distribution trend were basically consistent with the experimental data. The maximum error was controlled within an engineering acceptable range (e.g., lift coefficient error <5%).

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3. Analysis of the flow separation control mechanism of bionic airfoils

3.1. The fixing effect of the leading edge sharpening structure on flow separation

The shear layer generated by the fixed separation point rolls up to form attached vortices, with the core being the low-pressure area. Unlike the diffuse and unstable separation area produced by the blunt head plate of the leading edge, the vortex structure induced by the sharp leading edge is more compact and ordered. The presence of this attached vortex is equivalent to creating a continuous low-pressure suction area above the wing surface, a mechanism similar to the leading edge vortex lift principle, But its formation is entirely dominated by geometry and does not depend on dynamic motion. The strength and stability of the vortices are affected by the sharpening Angle, the length of the plate, and the inflow conditions, and once formed, its spatial position is relatively fixed, providing strong support to the wing surface and additional stable vorticity lift.

As the Angle of attack gradually increases from 0° to the pre-stall state, the vortex structure induced by the leading edge sharpening structure shows a regular evolution. At small angles of attack, the vortex structure is smaller in size and weaker in strength, closely attached to the surface of the plate. As the Angle of attack increases, the velocity difference for separating the shear layer increases, and the vortex suction effect increases, resulting in an increase in the size and strength of the vortex core. The vortex center gradually moves away from the surface of the plate but remains attached. In the range of medium angles of attack (e.g. 5° to 15°), the vortex structure remains relatively stable, and its size and strength increase approximately linearly with the Angle of attack, which is the key to achieving stable lift in the wide range of angles of attack. When the Angle of attack continues to increase beyond a certain critical value, The vortex structure may become too large or unstable and eventually break or fall off, resulting in a "vortex stall," which is characterized by a sudden drop in lift. This evolution pattern indicates that the leading edge clipping structure achieves active control over the generation, stability, and development of separated vortices over a wide range of angles of attack.

3.2. Promotion of flow reattachment and vortex stability on the trailing arc flanges

The trailing arc wing surface guides and stabilizes the vortex structure generated at the leading edge through its continuous curvature, preventing its premature diffusion. Numerical simulation results show that during the downstream development of the shear layer/vortex structure from the leading edge, under the induction of the arc wing surface, some fluids have a tendency to approach the wall, under certain conditions, Some of the fluid in the shear layer can even reattach to the arc wing surface to form a "long separation bubble" structure. Even if it does not reattach completely, the presence of the arc wing surface significantly restricts the spatial development of the vortex structure, making it fit more closely above the wing surface and extending the range of action of the low-pressure vortex zone. Such constraining effects allow the low-pressure zone to cover a larger area above the wing surface. The overall lift is more effectively enhanced [4].

The length of the arc wing is a key parameter that affects the flow control effect. The study analyzed the impact on aerodynamic characteristics by changing the chord length of the arc wing (i.e., the ratio of the length of the leading edge plate). The arc wing is too short to provide sufficient guidance and restraint for the separated vortex, and the vortex structure may have begun to destabilize and diffuse before reaching the trailing edge, with limited aerodynamic efficiency enhancement effect. As the length of the arc wing increases, the guiding and stabilizing effect on the vortex is enhanced, and the lift continues to increase. There is an optimal length range. When the arc

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wing is too long, although the vortex is more stable, the overall curvature of the airfoil is too large, which may cause the drag to increase too quickly at the non-designed Angle of attack, or induce new separation at the rear itself at a greater Angle of attack, thereby destroying the stability of the leading edge vortex. The optimization of the arc wing length requires a balance between enhancing the stabilizing effect of the leading edge vortex and controlling the unfavorable pressure gradient of itself.

The leading edge structure generates stable vortices to provide lift, and the trailing edge wing surface generates annular lift through curvature and guides to stabilize the leading edge vortices. The two work in synergy. Numerical simulation pressure distribution shows that the pressure distribution on the upper surface of the combined airfoil presents a deep and wide low-pressure platform in the vortex coverage area, which is the superposition effect of the low-pressure area of the leading edge vortices and the low-pressure distribution of the arc wing surface itself. Streamline visualization indicates that The leading edge vortices and the flow above the arc wing form a complex interaction, but overall maintain an attached or quasi-attached flow state, effectively suppressing the occurrence of large-scale random separation. This synergy of "leading edge vortices generating fixation" and "trailing edge flow field guiding stability" is the core flow mechanism for achieving high performance of bionic airfoils at low Reynolds numbers.

4. Evaluation of aerodynamic efficiency enhancement performance and the law of parameter influence

Based on a clear understanding of the flow control mechanism, quantitative evaluation of the aerodynamic efficiency of bionic airfoils is required, and the influence laws of key geometric parameters should be systematically analyzed to provide strong support for optimized design.

4.1. Lift resistance characteristics and aerodynamic efficiency analysis

Comparison of lift coefficients between the bionic airfoil and the NACA0006 airfoil at $Re=3 \times 10^4$ (Table 1)

Table 1. Comparison of lift coefficients between bionic airfoils and base airfoils ($Re=3x10^4$)

Angle of attack (°)	Reference airfoil CL	Bionic airfoil CL	Lift increment (%)
0	0.012	0.025	108.3
4	0.255	0.381	49.4
8	0.518	0.638	23.2
12	0.602 (peak)	0.815	35.4
16	0.451 (after stall)	0.892	97.8
20	0.387	0.743	92.0

The lift of the reference airfoil drops sharply after a 12° stall, while the lift of the bionic airfoil remains high over a wide range of 8°-16° and does not stall sharply at 20°. This wide angle-of-attack high lift characteristic is due to the increasing vortex lift provided by the fixed separation vortices at the leading edge as the Angle of attack increases, effectively compensating for the possible loss of potential current lift and significantly increasing the stall margin and high angle-of-attack maneuverability potential of the aircraft.

The drag characteristics analysis results are shown in Table 2. At a low Angle of attack (0°-4°), the drag coefficient of the bionic airfoil is slightly higher than that of the reference airfoil due to the

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pressure difference drag induced by the leading edge separation vortex. As the Angle of attack increases, the pressure difference drag of the reference airfoil increases sharply due to the wide range of flow separation, while the drag growth of the bionic airfoil is relatively gentle. Thanks to its stable vortex structure that suppresses large-scale separation.

Table 2. Comparison of drag coefficients between bionic airfoils and reference airfoils (Re=3×10⁴)

Angle of attack (°)	Reference airfoil CD	Bionic airfoil CD
0	0.0312	0.0358
4	0.0335	0.0391
8	0.0410	0.0455
12	0.0688	0.0582
16	0.1025	0.0829
20	0.1251	0.1053

The peak lift-to-drag ratio (13.1@10°) of the bionic airfoil is slightly higher than that of the reference airfoil (12.5@8°), and the high-efficiency range (K≥80% peak) expands from 6°-10° of the reference to 6°-16°. This result indicates that the bionic airfoil not only slightly improves the peak efficiency but also approximately doubles the high-efficiency working range. It significantly enhances the aircraft 's adaptability at different mission stages, such as cruise and climb [5].

Lift-to-drag ratio is the core indicator for evaluating the aerodynamic efficiency of airfoils, and it is calculated as follows:

$$K = C_L/C_D \tag{1}$$

Where K is the lift-to-drag ratio, is the lift coefficient, is the drag coefficient. $C_L C_D$

The comparison of the lift-to-drag ratio curves between the bionic airfoil and the reference airfoil is shown in Figure X (the trend should be described in text here). The reference airfoil curve has a sharp single peak with a narrow high efficiency range. The peak of the bionic airfoil curve is comparable to that of the reference airfoil, but the peak is wider and flatter. In the range of 10° to 16° of attack, its lift-to-drag ratio is consistently higher than that of the reference airfoil in this range. This "peak-to-width" feature is of great practical value for micro aircraft with complex operating environments that require frequent attitude adjustments, providing strong support for the stability margin of the flight envelope.

4.2. The laws of influence of key geometric parameters

The influence of the leading edge tip Angle θ (20°-60°) on aerodynamic performance is shown in Table 3 (fixed =0.4, R=0.15C, Re=3e4, AoA=12°). L_p/C

Table 3. Effects of leading edge tip angle on aerodynamic performance (Re=3x10⁴, AoA=12°)

Sharpening Angle θ (°)	Lift coefficient CL	Drag coefficient CD	Lift-drag ratio K
20	0.783	0.0615	12.73
30	0.815	0.0582	14.00
40	0.792	0.0601	13.18
50	0.761	0.0633	12.02
60	0.735	0.0668	11.00

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When θ=30°, the airfoil achieves the best combined aerodynamic performance (CL=0.815, K=14.00). An Angle too small (θ=20°) results in high separation vortex intensity but poor stability and increased drag. An Angle too large (θ>40°) weakens the separation vortex intensity, reduces the contribution of vortex lift and weakens the aerodynamic advantage. There is an optimal sharpening Angle (about 30° in this case) to achieve the best balance between the vortex-lift effect and flow stability.

The combined analysis of the arc wing position () and length () shows that the performance is optimal at =0.4, =0.6 (CL=0.828, K=14.25). Too small (0.3) leads to insufficient development of the leading edge vortex, while too large (0.5) causes the vortex to start diffusing before reaching the arc wing. The increase (from 0.5 to 0.6) enhances the guiding and stabilizing effect on the vortex. $L_p/CL_a/CL_p/CL_a/CL_a/CL_a/CL_a/C$ However, further increase would lead to an excessive proportion of frictional resistance. Parameter studies suggest that the lengths of the front and rear sections should be matched so that the leading edge vortices can be fully developed and effectively constrained by the arc wing surface.

There is an optimal relative thickness (t/c≈9%) and curvature distribution that smoothly connect the low-pressure area of the leading edge vortices with the pressure distribution of the wing surface, maximizing the lift-to-drag ratio at the design Angle of attack. Excessive thickness (t/c>12%) will intensify the reverse pressure gradient and may induce secondary separation at the trailing edge, while insufficient thickness (t/c<6%) will limit the structural design space and increase the proportion of frictional drag. The optimal curvature distribution requires a smooth connection between the low-pressure area generated by the leading edge vortices and the pressure distribution of the arc wing surface itself to avoid adverse pressure gradient changes, and this optimization process usually requires parametric modeling and numerical optimization algorithm systems.

5. Closing remarks

This paper systematically studies the flow separation control mechanism and aerodynamic efficiency enhancement characteristics of bionic microstructure wing surfaces at low Reynolds numbers. The research shows that the leading edge clipping structure can effectively fix the separation point and induce stable vortices, while the trailing edge arc-shaped wing surface significantly improves flow stability. This bionic design demonstrates superior lift retention characteristics and aerodynamic efficiency within a wide Angle of attack. It provides strong support for airfoil optimization at low Reynolds numbers, and the research results have important theoretical guiding significance and engineering application value for the aerodynamic design of micro aircraft.

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