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A Review of Innovative Research on Airfoil in Wide-velocity Aircraft

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Abstract: The aircraft has undergone sub/span/super/hypersonic flight, and the aerodynamic characteristics of different speed domains are obviously different, and the aerodynamic focus of the whole aircraft changes greatly, making it difficult to design stability matching. In order to achieve horizontal take-off and landing, high lift is required when flying at low Mach number, and high lift-to-drag ratio is required when flying with high Mach number, and the contradiction of demand further increases the difficulty of designing aircraft in the wide speed range. This paper will explore the impact of the design and selection of aircraft wing airfoils on the performance of flight situations. The results of the study showed: when using airfoil NPU-Hyper-04:At low speeds, the efficiency of the lift generated by the wing rises. When employing a new airfoil with double "S" characteristics, the overall aerodynamic performance of the wing with the new airfoil is superior within the wide speed range, indicating that the designed airfoil for the wide speed range is on the three-dimensional wing. It also has certain practical value. When using variable wingtips, the wingtip folds downward, resulting in a wave-riding effect and a forward shift of the aerodynamic center.

Keywords: Wide speed range design requirement, airfoil design, wing design, Variable wingtips, Pneumatic characteristics

1. Introduction

The aircraft has undergone sub/span/super/hypersonic flight, and the aerodynamic characteristics of different speed domains are obviously different, and the aerodynamic focus of the whole aircraft changes greatly, making it difficult to design stability matching. In order to achieve horizontal take-off and landing, high lift is required when flying at low Mach number, and high lift-to-drag ratio is required when flying with high Mach number, and the contradiction of demand further increases the difficulty of designing wide-speed aircraft metering method. According to public literature reports, there are two main methods of aerodynamic design in the wide speed range: one is to adopt the aerodynamic layout of the variant, such as the plane shape of the wing is changing, and the aerodynamic shape of the variant aircraft is changed according to the needs to meet the requirements of the wide speed range flight, but the structure and control system are complex, especially the structural thermal protection under hypersonic speed is more difficult to achieve, although the research on variant aircraft in foreign countries has made some progress [1-2], there is still a big gap from engineering practicality, and there are still many key technologies to be solved. Another design

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method is to adopt a fixed configuration aerodynamic layout , and to meet the design requirements of a wide speed range by optimizing the aerodynamic shape, which has the advantage of reducing the difficulty of structural thermal protection design. This research concentrates on the wide-velocity domain aerodynamic layout of the vortex effect proposed for the fixed-configuration aircraft. It is believed that the low-speed and hypersonic aerodynamic performance can be taken into account through the reasonable design of the fixed-plane waverider. However, there is still a big gap between current waverider design and application of engineering, and it is difficult to meet the engineering design requirements of wide-speed aircraft only through the vortex effect after considering the overall index constraints such as aircraft volume and lift-weight matching. As we all know, the wing is the main lifting component of conventional aircraft, which directly affects the take-off and landing performance and handling quality of the aircraft, so the design and optimization of the wing and airfoil is an important research content of the aerodynamic layout of the airplane. [4]. It is a new design idea to apply the new airfoil and solve the design problem of the wide speed flight of the aircraft through the optimized design of the aerodynamic shape. In recent years, Han Zhonghua et al. [5] have proposed a wide-velocity airfoil (NPU-Hyper-04) that takes into account the aerodynamic characteristics of low-speed and super/hypersonic speeds, which has a certain curvature, a flat upper surface and a double "S" shape on the lower surface. It is applied to aircraft. For the large swept wing of the aircraft, the three-dimensional effect of the wing has a significant impact, and it is necessary to carry out the analysis of the aerodynamic characteristics of the wing and airfoil in the wide speed range under the three-dimensional flow, and the research on the engineering application of the new wing. For variable wingtips, in the 70s of the 20th century, the XB-70, a large supersonic strategic bomber, adopted a folding wingtip design to achieve a significant increase in overall performance[6]. Studies have shown that the XB-70 has a waverider design, with the wingtips folding down to allow the underside of the wing. Generates a larger compression wave, which increases wing lift; It can improve the stability of the transverse course and reduce the induced resistance. The effective wing area close to the trailing edge is reduced when folded down, which reduces the amount of correction for the transonic focus backward shift and improves transonic stability. However, due to the discontinuous deformation of the wingtip and the large gap at the folding position, the aerodynamic performance loss and noise are large. The flexible wingtip has continuous deformation and small airflow disturbance, which is conducive to noise reduction and has aerodynamic advantages. In recent years, the technology of flexible wingtips has been continuously developed, and a variety of structural forms have been experimentally verified [7], but they have not yet been applied to the aerodynamic layout design of supersonic civil aircraft. Regarding the influence of flexible wingtips on the wing characteristics of supersonic civil aircraft, there is still a lack of detailed theoretical research at home and abroad, and further in-depth research is urgently needed. The purpose of this paper is to design the wing airfoil for a wide-speed aircraft to ensure the aircraft performs optimally in a given flight situation. The research idea of this paper is to explore aerodynamic characteristics, application value, and optimization of the new airfoil based on the literature. Then, the effect of adding variable wingtips to the wings on the performance of the aircraft was investigated.

2. Current problems

The lift generated by a supersonic airfoil is not enough to be used effectively at subsonic speeds, whereas a subsonic airfoil produces more drag than lift at supersonic speeds. When a fixed geometry is used at supersonic and subsonic speeds, it creates inefficient flight.

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3. Solutions

3.1. NPU-Hyper-04 wide-speed domain airfoil.

It is a wide-velocity domain airfoil (NPU-Hyper-04) that takes into account the aerodynamic characteristics of low-speed and super/hypersonic speed, which has a certain curvature, the upper surface is relatively flat, and the lower surface has double "S" shaped characteristics, and the two-dimensional wing numerical simulation study of Han Zhonghua et al. [5] proves that the wide-speed domain airfoil has good aerodynamic characteristics and is expected to be applied to aerospace vehicles.

When an aerospace vehicle is flying at hypersonic speed in the atmosphere for a long time, the thermal environment at the leading edge of the wing is the most severe [8], and the temperature gradient is also large. It will bring difficulties to the design of structural and thermal protection. If the radius of the leading edge of the wing is small, the aerodynamic drag is small, but the thermal stress is concentrated, which makes the wing structure hot. There is a risk of destruction in the protection; If the radius of the leading edge of the wing is large, the thermal environment will be reduced, but the drag will be increased. Therefore, the demand for heat reduction and drag reduction on the leading edge of the wing is contradictory, and the radius of the leading edge of the wing needs to be compromised. According to the design experience of high-speed aircraft in the past, considering the design requirements of structural thermal protection, the radius of the leading edge of the airfoil can be selected as 0.05%~0.2% of the chord length. In addition, airfoils usually have a certain thickness to meet the strength design requirements of the wing [9]. In general, for subsonic transport aircraft, the maximum relative thickness of the airfoil is selected as 12%~18%, which can obtain a larger lift coefficient. For supersonic aircraft with swept wings, the airfoil is the largest. The relative thickness is about 10% to meet the requirements of the swept wing for structural strength design. For conventional supersonic aircraft, the maximum relative thickness of the airfoil is mostly in the range of 2%~6%. For hypersonic vehicles, in order to reduce wave resistance, theoretically speaking, the relative thickness of the airfoil should be as thin as possible, but considering the feasibility of structural thermal protection, it is recommended that the maximum relative thickness of the wide-velocity airfoil can be 2%~6% of the chord length. In addition, considering the existing machining accuracy, it is recommended that the thickness of airfoil's trailing edge should not be less than 0.8% of the chord length.[12]

Taking into account the thermal protection design requirements leading edge's structure, when the radius of the leading edge of the wing is 0.1% of the chord length and the maximum relative thickness is 4% of the chord length, Figure 1 presents the comparison between the wide velocity domain airfoil (NPU-Hyper-04) and the conventional airfoil shape.[12] As can be seen from the figure, the characteristics of the wide-speed airfoil are: the upper surface adopts a fuller head profile, and the lower speed can obtain better lift characteristics; The lower surface has the shape of double "S", the leading edge anti-"S" shape forms a front load at transonic speed, which can increase the lift, and an isentropic compression wave is formed at hypersonic speed, which can reduce the wave resistance and improve the lift-to-drag ratio. The "S" shape of the trailing edge, which forms a rear load at transonic speed, can increase lift, while at hypersonic speed, it forms a "secondary high pressure", which is conducive to increasing lift. In addition, compared with the traditional typical airfoil, the lower surface of the wide-speed airfoil is a double "S" shape, and the curved surface shape is complex, which makes the structural design more difficult.

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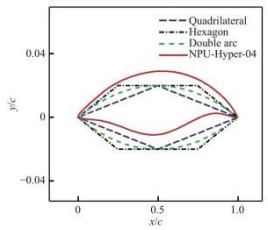

Figure 1: Comparison of different airfoil geometries

Figure 2 shows the plane shape of a double delta wing. The NPU-Hyper-04 wide-speed airfoil, quadrilateral, hexagonal and double-arc airfoils were applied to the double delta wing, and the lift coefficient and lift-drag ratio of the four wings were obtained with Mach number as shown in Figure 3. For example, when Ma = 0.2, the lift coefficient of the wide-speed airfoil is increased by 45.9% compared with that of the quadrilateral airfoil, 50.5% compared with the hexagonal airfoil, and 32.4% compared with the double-arc airfoil. When Ma = 0.8, wide-velocity airfoil's lift drag is increased by 57.7% compared with the quadrilateral airfoil, 63.9% compared with the hexagonal airfoil, and 63.9% higher than that of the double-arc airfoil 89.1%;When Ma = 1.5, the lift drag of the wide-speed airfoil is 9.8% higher than that of the quadrilateral airfoil, 28.3% higher than that of the hexagonal airfoil, and 21.3% higher than that of the double-arc airfoil. When Ma = 6, the lift-to-drag ratio of the wide-speed airfoil is 7.6% higher than that of the hexagonal airfoil, and 1.8% higher than that of the double-arc airfoil, but slightly lower than that of the quadrilateral airfoil, and the lift-to-drag ratio is reduced by 3.1%.[12]

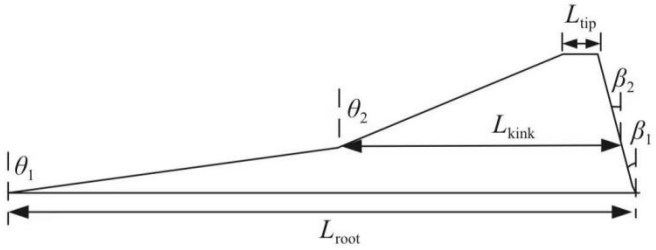

Figure 2: Sketch of double-triangle wing

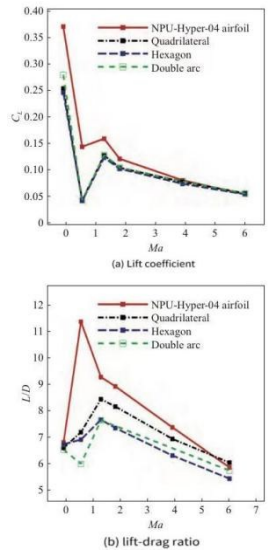

Figure 3: Variations of CL and L/D as a function of Ma for wings with different airfoils

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In summary, the NPU-Hyper-04 wide-speed airfoil has a high lift-to-drag ratio at sub/span/super/hypersonic speeds, which is consistent with the requirements of low-speed and high-lift and high-speed and high-speed high-lift-to-drag ratios of aerospace vehicles, and has a good engineering application scenario.

Compared with the traditional airfoil, the lower surface of the wing is more complex, which will bring certain difficulties to the preparation of structural thermal protection, which is an obvious disadvantage of the airfoil.

3.2. Using The three-dimensional wing optimization design method to optimize the NPU-Hyper-04 airfoil.

The three-dimensional wing optimization design method adopts the method of combining the parameterization of the plane shape of the wing with the parameterization of the airfoil at the three stations of wing root, wing turn and wing tip to realize the three-dimensional parametric modeling of double delta wing's shape.

The plane shape of the double delta wing can be uniquely determined by the swept angle of the leading edge of the inner wing (θ1), the swept angle of the leading edge of the outer wing (θ2), the ratio of chord length at the turning point of the wing to the length of the root chord (Lkink/Lroot), the slight ratio of the root (Lroot/Ltip), the swept angle of the inner wing's trailing edge (β1), the swept angle of the trailing edge of the outer wing (β2), and the wing area.[12]

The authors of research team used the multi-objective multi-constraint optimization software "SurroOpt" [10] based on the surrogate model to optimize the wing design in the wide velocity domain under three-dimensional flow, and the process is as follows: firstly, based on the defined optimization objectives, design variables and constraints, the geometric parametric modeling is carried out, secondly, the parametric model is meshed and the CFD three-dimensional flow field is calculated, and then the real objective function's surrogate model is established with the obtained sample dataset through post-processing. The optimal solution is approached step by step, and finally after comprehensive evaluation, the optimization process ends when certain termination conditions are met.

Through the elaboration and analysis of the above optimization methods, the optimization results can be obtained next:

A double delta wing based on the NPU-Hyper-04 wide-speed airfoil, denoted as the Case0 baseline state, is optimized for the following three states. The first is the use of the NPU-Hyper-04 wide-speed domain airfoil, along the aircraft. The airfoil shape of the wingspan direction does not change, and the plane shape of the optimized design wing is recorded as Case1 optimization state; The second is that the plane shape of the wing remains unchanged, and the airfoil is optimized designed, and the airfoil changes along the span direction of the wing, which is recorded as the Case2 optimization state; The third is that the airfoil shape and wing plane shape along the wing span can be changed, that is, the wing/airfoil integrated optimization design, which is recorded as the Case3 optimization state.[12]

Fig. 4(a)~(c) shows the airfoil shapes' comparison obtained under different optimization conditions at the wing roots, wing rotation and wing tips, respectively. As can be seen from the figure, the shape of airfoil at wing root, wing transition and wing tip is quite different under the same optimization target, and the airfoil obtained in the optimized state of Case2 and Case3 changes along the span of the wing.

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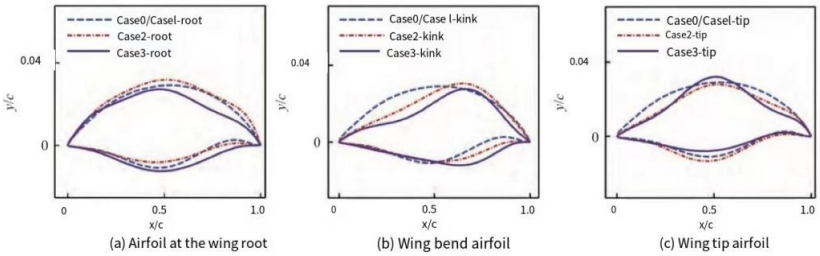

Figure 4: Comparisons of airfoil geometries obtained by different optimization methods at three locations of a double-triangle wing

Fig. 5(a)~(d) shows the surface pressure coefficient of the wing and vorticity at Cp= −1.2 in the benchmark state and the three optimized states, respectively. As you can see from the graph, Case1 and Case2 are optimized relative to the baseline state. The wing area was reduced by 37.2%, and the Case3 optimized wing area was reduced by 36.3%. The upper surface of the wing in the three optimized states generates strong vortex flow, which is beneficial for enhancing the lift in the low-speed take-off state, that is, the lift generated by the wing per unit area.[12].

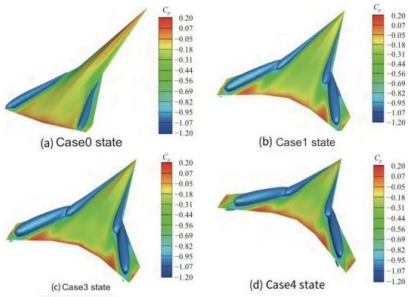

Figure 5: Comparisons of surface pressure and vorticity (Cp = −1.2) obtained by different optimization methods at Ma = 0.3

Figure 6(a)~(b) shows the lift-to-drag ratio of the lift-to-weight balance during supersonic and hypersonic flight in different states, and the abscissa is the ratio of lift to the take-off gravity of the aircraft. The results show that the lift-to-drag ratios of supersonic and hypersonic in the three optimized states are increased compared with the benchmark state Case0, and the lift-to-weight balance lift-to-drag ratios in the Case1optimization state are increased by 11.9% and 2.7%, respectively. In case 2, the lift-to-weight balance lift-to-drag ratio increased by 19.5% and 8.8%, respectively. The Case3 has the best optimization results, with a lift-to-weight balance lift-to-drag ratio improvement of 33.5% and 12.9%, respectively, especially in hypersonic flight, where the flight angle of attack is close to the angle of attack corresponding to the maximum lift-to-drag ratio.[12]

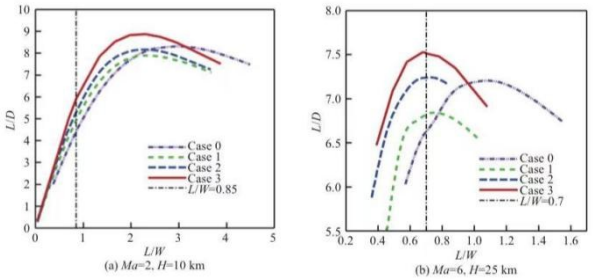

Figure 6: Lift-weight-balance L/D at different fight status

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To sum up, for the Case1 optimization state, the fixed airfoil shape and optimized wing plane shape can be used to meet the lift in different speed domains Beg. For the Case2 optimization state, the plane shape of the wing is determined, and the airfoil shape of each section of the wing is optimized to improve the lift-to-drag ratio in the wide speed range. For the Case3 optimization state, the airfoil shape of the wing plane shape and the typical position of the wing can be optimized, and the wing with better comprehensive performance in the wide speed range can be obtained, and the wing area is small, the lift efficiency is high, and the lift-to-drag ratio is high during super/hypersonic flight.

3.3. Using variable wingtips to improve the aerodynamic characteristics of supersonic civil aircraft wings

The aerodynamic layout design of supersonic civil aircraft is contradictory in the configuration during the low-speed take-off and landing and high-speed cruising stages, and the design of variable wingtips has emerged as one of the feasible solutions.

In the 70s of the 20th century, the XB-70, a large supersonic strategic bomber, adopted a folding wingtip design to achieve a significant increase in overall performance[6]. Studies have shown that the XB-70 adopts a waverider design, and the wingtip folding down can cause a larger compression wave on the lower surface of the wing, which increases the lift of the wing. It can improve the stability of the transverse course and reduce the induced resistance. The effective wing area close to the trailing edge is reduced when folded down, which reduces the amount of correction for the transonic focus backward shift and improves transonic stability. However, due to the discontinuous deformation of the wingtip and the large gap at the folding position, the aerodynamic performance loss and noise are large. The flexible wingtip has continuous deformation and small airflow disturbance, which is conducive to noise reduction and has aerodynamic advantages.

Referring to the folding position and wingtip chamfer angle of the XB-70 [11], the research team of the literature selected the folding position of the wing tip at 40% from the wingtip, folded the folding wingtip down 20°, 40°, and 60°, and the flexible wingtip folded down 20°, 30°, 40°, and 60°, respectively, to establish the folding wingtip wing model and the flexible wingtip wing aerodynamic model, as shown in Figure 7.[13]

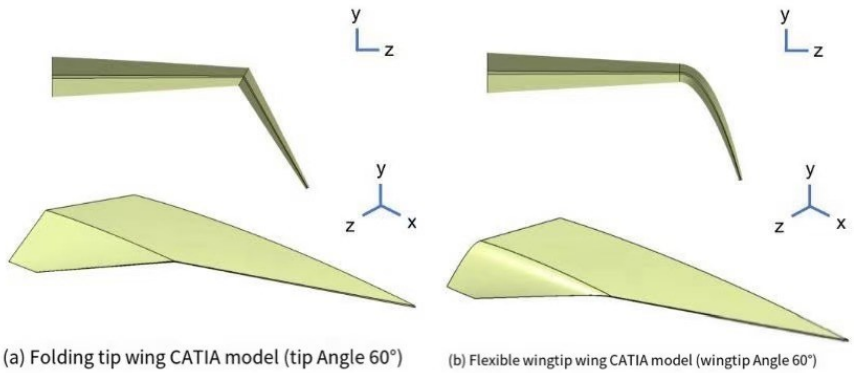

Figure 7: Variable wingtip wing aerodynamic model

Combined with the literature, this study finds: The lift-drag characteristics of folded wingtip wings are as follows: (1) With the increase of wingtip chamfer angle, the lift coefficient of the wing decreases, the drag coefficient decreases, and the lift-drag ratio decreases; (2) When the wingtip fold angle is small, the wingtip downward fold has little effect on lift-resistance characteristics; (3) Under

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different flight angles of attack, the lifting resistance characteristics are basically the same with the wingtip angle.

Compared to the lift-resistance characteristics, the downward folding of the wingtips has a greater effect on the aerodynamic center of the wing. The variation law of the center of pressure of the folded wing tip wing is as follows: (1) The downward folding of the wing tip will result in the forward movement of the wing center. With the increase of the wing tip angle, the amount of forward movement of the center will be greater. (2) Under different flight angles of attack, the variation law of the center position with the wingtip angle is basically the same. The larger flight angle of attack, the smaller the amount of forward movement of the center.

The effect of the flexible wingtip down-fold on the lift drag is basically the same as that of the folded wingtip down-folding. The wingtip chamfer angle increases, the lift coefficient decreases, and the drag coefficient decreases. Unlike folding wingtip wings, the lift-to-drag ratio of flexible wingtip wings increases when the wingtip chamfer angle is smaller; When the wingtip chamfer angle is large, the lift-to-drag ratio of the flexible wingtip wing decreases. It can be seen that flexible wingtips have more aerodynamic advantages than folding wingtips.

The authors' team conducted a comparative analysis of the pressure contour diagram of a folding wingtip wing with a wingtip angle of 40° and a flexible wingtip wing in Fig. 8. I found that the high-pressure area at the front end and the low-pressure area at the rear end of the lower surface of the flexible wingtip wing are smaller than those of the folding wingtip wing, indicating that the flexible wingtip down-folding has less disturbance to the airflow and has more aerodynamic advantages. The authors' team conducted a comparative analysis of the pressure contour diagram of a folding wingtip wing with a wingtip angle of 40°and a flexible wingtip wing. I found that the high-pressure area at the front end and the low-pressure area at the rear end of the lower surface of the flexible wingtip wing are smaller than those of folding wingtip wing, indicating that the flexible wingtip down-folding has less disturbance to the airflow and has more aerodynamic advantages.

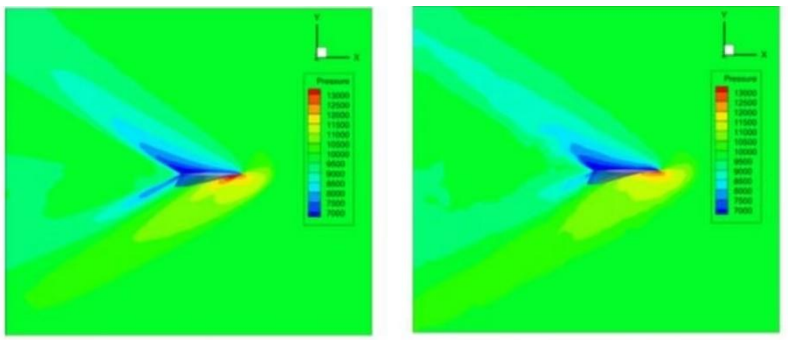

Figure 8: Comparison of pressure contours

4. Conclusion

Through the above innovative research and optimization of the wide-speed airfoil and the application of variable wingtips, this study finds the following: Firstly, through the integrated optimization design of the wide-speed airfoil and the plane shape of the wing, a new wing shape with excellent aerodynamic characteristics is obtained. Compared with the pre-optimized wing, the lift efficiency of the wing increases by 36.3% at low speed, and the lift-to-weight balance lift-to-drag ratio of supersonic and hypersonic increases by 33.4% and 12.9% respectively. Especially in hypersonic flight, the flight angle of attack is close to the maximum lift-to-drag ratio corresponding to the angle of attack. Secondly, Compared with the traditional airfoil, the lower surface of the wing is more complex, which will bring certain difficulties to the preparation of structural thermal protection. In

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the follow-up research work, the thermal environment changes brought about by the application of the new wing will be further evaluated. At last, The wave-riding effect of the wingtip folding down will produce a high-pressure area under wing, which reduces the lift loss caused by the reduction of the wing area, and has certain aerodynamic advantages; The downward folding of the wingtip will make the center position of the wing move forward obviously, and the change of the aerodynamic center caused by the cross-speed domain can be reduced by adjusting the wingtip folding angle, so as to effectively improve the operation of the aircraft longitudinal performance; Flexible wingtips have more aerodynamic advantages than folding wingtips.

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