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Analysis of Aerodynamic Characteristics of Various Airfoils under Subsonic Flow under Ground Effect

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Abstract: In this comprehensive study, we utilize ANSYS Fluent, a sophisticated fluid dynamics simulation tool employing the finite volume method, to address intricate aerodynamic computations. Leveraging ANSYS Meshing, we meticulously craft precise geometric models and meshes for airfoils, ensuring the fidelity of our simulations. This meticulous attention to detail is crucial for accurately capturing the complex aerodynamic phenomena involved in ground effect scenarios. Our research delves into the aerodynamic attributes of various airfoils, particularly under subsonic ground effect conditions. We conduct a rigorous comparative analysis of the pressure distribution, drag coefficient, and lift coefficient for the NACA4412, NACA0012, and RAE6-9CK airfoils. By analyzing these parameters, we gain a deeper understanding of how different airfoil designs interact with the ground, which is essential for optimizing the performance of ground-effect aircraft. The insights derived from this analysis are pivotal for refining the design of ground-effect aircraft. They reveal areas for improvement in current designs and guide the development of new aircraft models. Additionally, these insights underpin the rigorous development and testing of novel aircraft models, ultimately enhancing their performance, efficiency, and operational prowess. Overall, this research contributes significantly to the progression of aerospace engineering and the aviation sector. It provides a foundation for future research and development efforts in ground-effect aircraft and has the potential to lead to significant advancements in the performance and efficiency of these aircraft.

Keywords: ground effect, airfoil, aerodynamic characteristic, subsonic, numerical simulation

1. Introduction

Ground effect refers to a kind of phenomenon in which the ground interferes with the aerodynamic characteristics of an object when it moves near the earth. On the one hand, when the aircraft moves near the planet, due to the existence of a ground boundary, the airflow under the wing will be blocked, and the kinetic energy of the airflow will be converted into pressure potential energy, thus increasing the lift of the wing. Also, the ground effect can significantly reduce the induced drag of the wing, thereby increasing the lift-drag ratio of the aircraft.

Research on ground effects began in the 1920s. In the 1980s, the Soviet Union successfully tested a large ground-effect vehicle, the Caspian Monster, to strengthen its offshore military forces. The ground effect aircraft has the characteristics of strong airworthiness, high cruising speed, low cost,

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and wide application. In recent years, with the rapid development of aviation science and technology, many countries have begun to pay attention to the important role of ground-effect aircraft in ocean traffic and military purposes.

At present, the research on the two-dimensional airfoil lift effect under the action of ground effect is relatively extensive. Hsiun and Chen studied the effects of Reynolds number, flight altitude, and Angle of attack on the aerodynamic characteristics of the NACA4412 airfoil through numerical simulation [1]. It is found that the channel shape formed between the airfoil and the ground determines the influence of the ground effect on the aerodynamic characteristics of the airfoil. Ahmed and Takasaki studied the aerodynamic characteristics of the NACA4412 airfoil at different angles of attack and flight heights through wind tunnel tests with moving ground [2]. They found strong suction and laminar flow separation at the trailing edge of the wing at 0° Angle of attack. For 4° and above the Angle of attack, lift and drag increase the closer the wing is to the ground. Qu and Wang studied the lift characteristics of the airfoil in the range of Angle of attack from -4° to 20°and divided the Angle of attack and flight height into three intervals according to the increased value of lift, namely, one positive ground effect zone and two negative ground effect zones [3]. Only in the positive ground effect zone can the wings achieve increased effects due to ground effects. Doig numerically studied the influence of ground effects on transonic and supersonic wings and analyzed the reflection of shock waves and the interaction between shock waves and wing wake [4]. Liu numerically studied the aerodynamic characteristics of different airfoils under subsonic ground effects [5].

In the design of ground effect aircraft, the selection of airfoil is particularly important because of the need to give full play to its load advantage, further improve fuel efficiency, and enhance the stability of ground effect aircraft in near-earth flight. Three airfoils are selected in this paper, namely, NACA4412, NACA0012 and RAE6-9CK. The three airfoils are different in shape. The upper surface of NACA4412 is curved, and the lower surface is flat. NACA0012's upper and lower surface curvature is similar; The upper surface of RAE6-9CK is relatively flat, and the lower surface is curved. The aerodynamic characteristics of the three airfoils' underground effects need to be further studied. The design speed of ground-effect aircraft in service so far is generally about 300km/h. Many studies have focused on the comparison of aerodynamic characteristics of airfoils under ground effect at low speed, but little research has been done on aerodynamic characteristics of airfoils with different characteristics under ground effect at high speed. When the incoming flow speed reaches Ma=0.5, the air will show compressibility and even local supersonic will appear, and the lift-drag characteristics of the wing of the ground affect aircraft will change greatly. The aerodynamic characteristics of the high-speed ground effect vehicle need to be further studied, such as the influence of flight altitude parameters. This paper analyzed the ground effect aerodynamic characteristics of three airfoils at different flight speeds based on ANSYS Fluent fluid simulation software.

2. Methodology

2.1. Geometric models and computational domains

In this paper, NACA4412, NACA0012, and RAE6-9CK are selected as the research objects. The geometry for the simulation is created by importing airfoil data into Fluent. The geometry of NACA4412, NACA0012, and RAE6-9CK is shown in Fig.1. And Fig 2 shows the computational domain used for computational simulation [6]. The specified inlet is a speed inlet, while the outlet is a pressure outlet.

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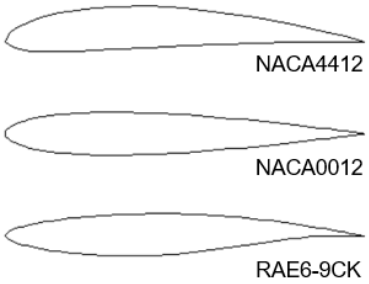


Figure 1: Geometric models of NACA4412、NACA0012 and RAE6-9CK

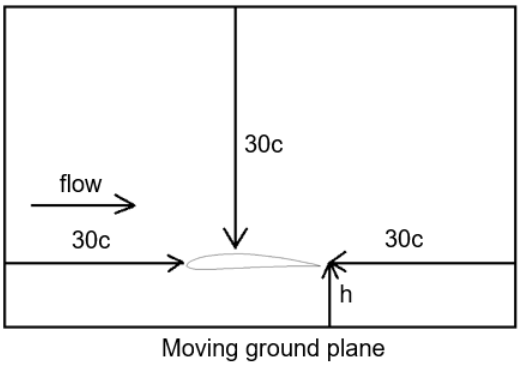


Figure 2: Computational domain

2.2. Mesh generation

This paper selects the 2D structured mesh to generate the mesh for the airfoil and computation domain. To better simulate the flow field motion, the quadrilateral calculation domain is used in the figure. The entrance, exit, and upper boundary of the computational domain are all positioned 30c away from the airfoil. The travel height h represents the distance between the ground and the trailing edge of the airfoil. A longer unit length is used for grid generation in the outer area to improve computing efficiency and reduce computing costs. A fine mesh is used around the airfoil to better reflect fluid movement. The number of grids in the calculation domain is about 32,000. The grid division in the calculation domain is shown in Fig.4. Local details around the airfoil are shown in Fig.5.



Figure 3: Mesh of overall domain

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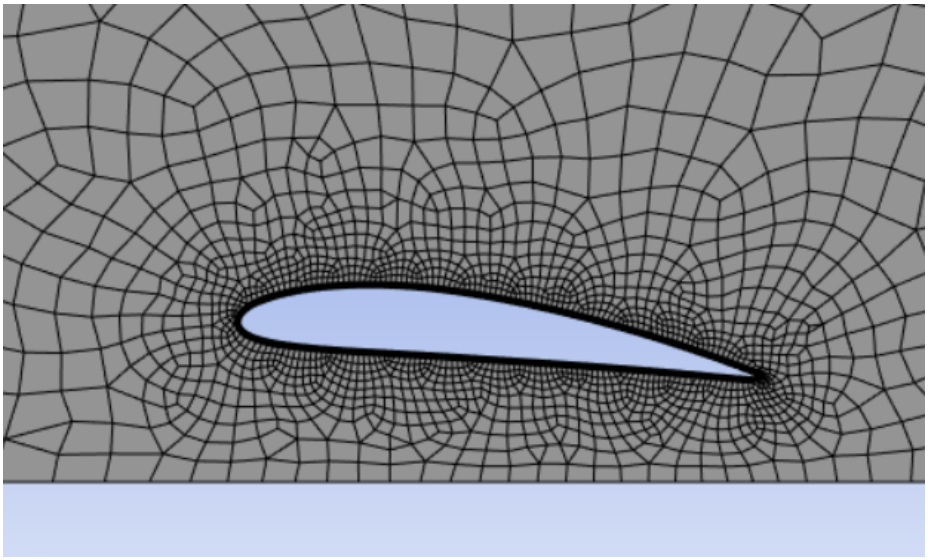


Figure 4: Detail of airfoil mesh

2.3. Boundary conditions and governing equations

Boundary conditions refer to the characteristic physical properties or conditions on the surface of a region that represent a specific flow variable of a physical model. To obtain accurate numerical results, this paper sets 1000 iterations and 10-6 iteration errors during CFD simulation to ensure the convergence of results. The ground boundary condition is configured as a sliding wall, while the inlet, outlet, and upper limit are set as far-field pressure boundary conditions. The basic governing equation used in this paper is the Reynolds mean Navier-Stokes equation of compressible steady flow. The expression of the equation is as follows:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[u\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial u_i}\right) - \overline{\rho u_i' u_j'}\right] \quad (1)$$

$\overline{\rho u_i' u_j'}$ refers to Reynolds stress. The RANS equation is solved by the Realizable k-ε turbulence model, and the wall strengthening function is applied in the near-wall region of the flow field. The Realizable k-ε turbulence model adds a new transport equation for the turbulent viscosity and a new transport equation for the dissipation rate, which can more accurately simulate rotational uniform shear flow, free flow and boundary layer flow [6,7].

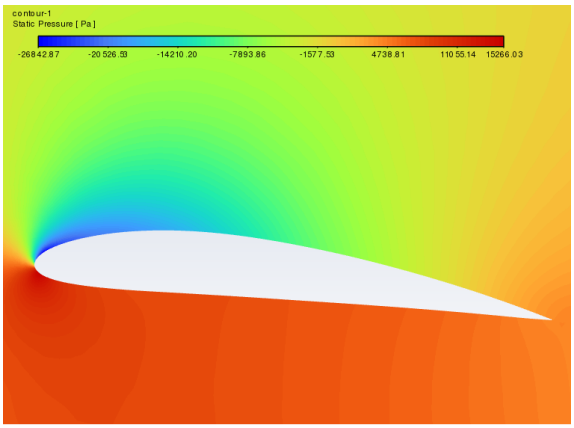
3. Results and discussion

In this paper, three airfoils are solved in detail based on Fluent software, and their aerodynamic characteristics and underground effects are studied.

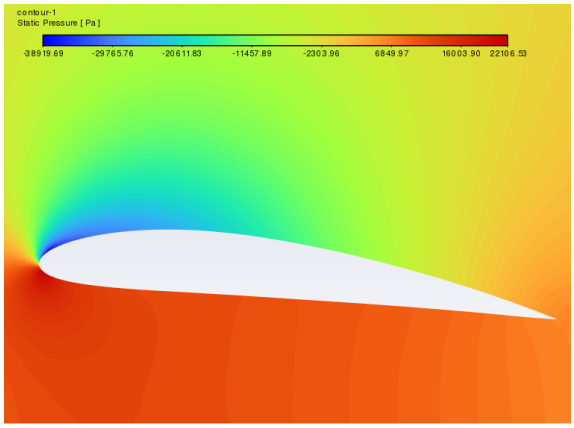
For subsonic airfoil NACA4412, NACA0012, and transonic airfoil RAE6-9CK (Fig. 1), the aerodynamic characteristics under different incoming velocities are compared and analyzed. As shown in Fig. 5, the flow field pressure distribution around the airfoil shows that the airflow pressure between the lower airfoil of RAE6-9CK and the ground is significantly higher than that of the other two airfoils. This is due to the contraction of the airflow channel between the latter and the ground. When Ma=0.5, the small leading-edge radius of RAE6-9CK airfoil makes the airflow deflection Angle larger, and the leading-edge airflow velocity rapidly increases beyond the sound velocity, resulting in shock wave resistance and rapid increase of its drag coefficient. In the case of Ma=0.6 incoming flow, as shown in Fig. 6 the shock wave strength of the NACA4412 airfoil is weaker than

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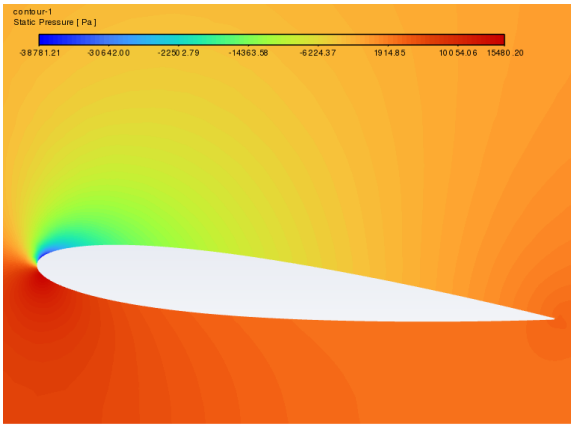
that of the other two airfoils, and the shock wave position is backward, so the shock wave resistance is smaller.



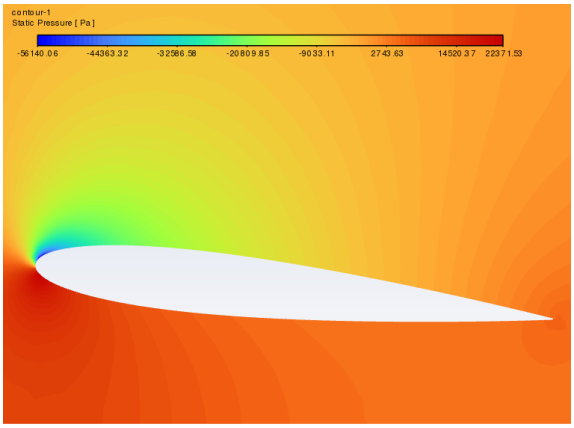
(a)Ma=0.5 NACA4412



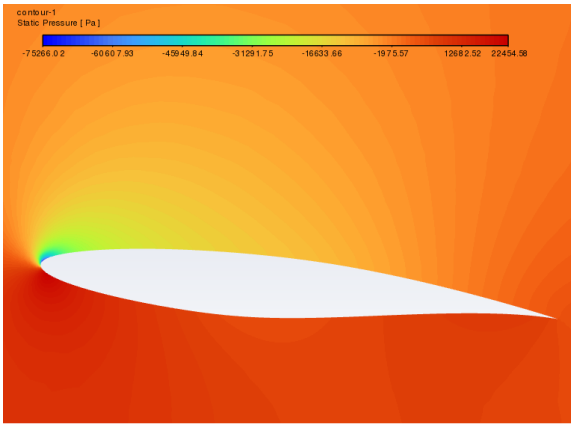
(b)Ma=0.6 NACA4412



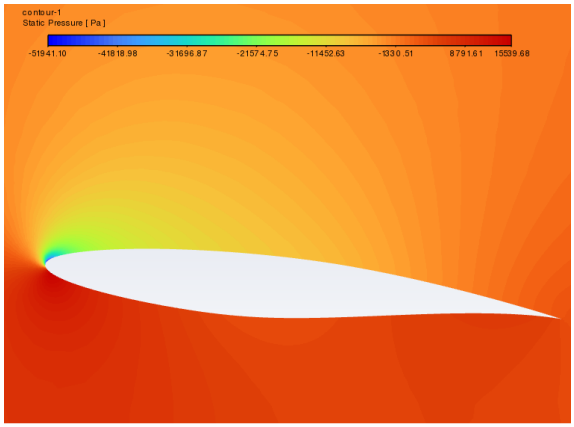
(c)Ma=0.5 NACA0012



(d)Ma=0.6 NACA0012



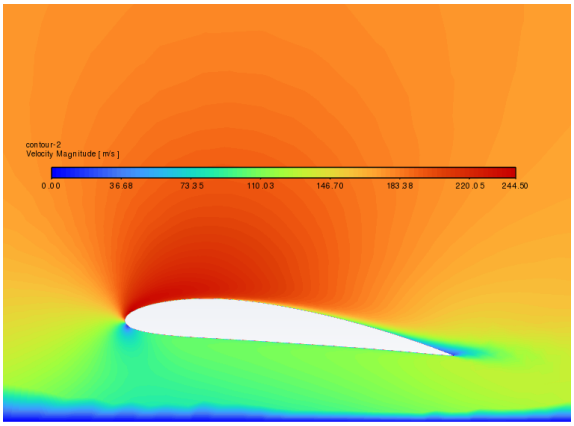
(e)Ma=0.5 RAE6-9CK



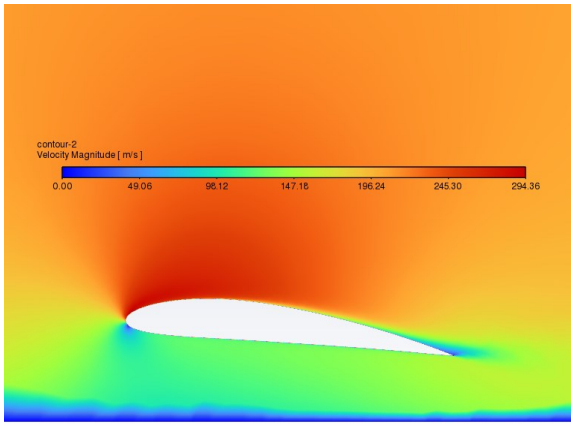
(f)Ma=0.6 RAE6-9CK

Figure 5: The pressure distribution in the flow field under the inflow conditions with Ma=0.5 and 0.6

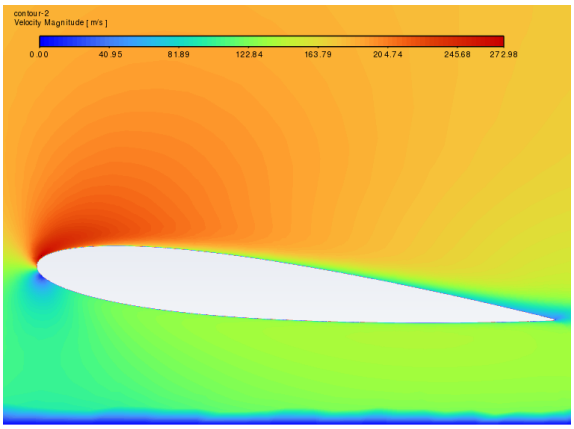
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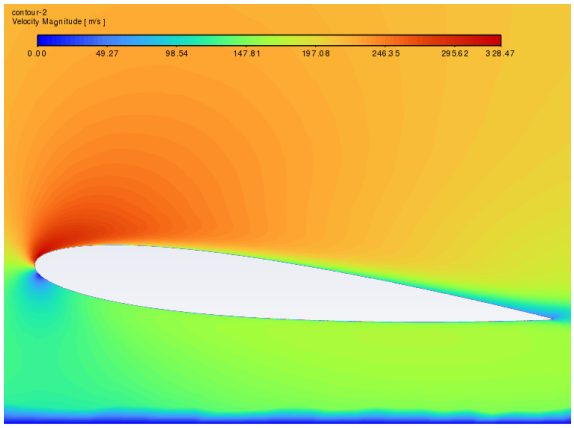
(a)Ma=0.5 NACA4412



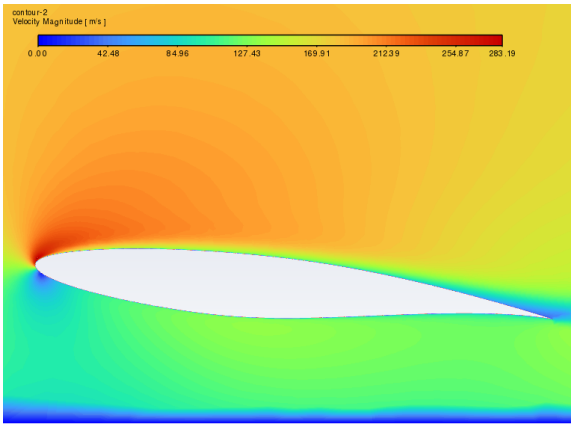
(b)Ma=0.6 NACA4412



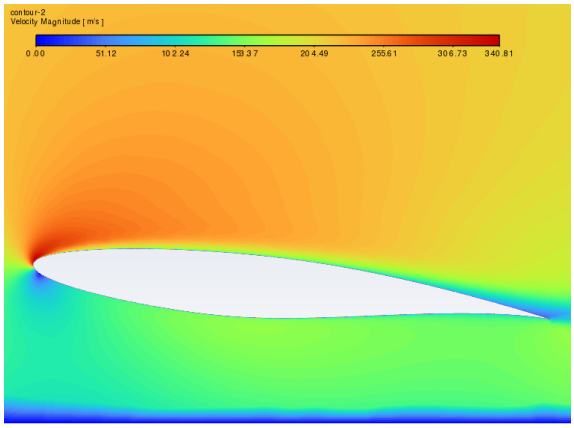
(c)Ma=0.5 NACA0012



(d)Ma=0.6 NACA0012



(e)Ma=0.5 RAE6-9CK



(f)Ma=0.6 RAE6-9CK

Figure 6: The velocity distribution in the flow field under the inflow conditions with Ma=0.5 and 0.6

As shown in Fig.7, with the increase of incoming Mach number, the lift coefficients of the three airfoils all increase to varying degrees, and the lift coefficients of NACA4412 increase rapidly between Ma=0.3 and 0.4. Compared with NACA0012 and RAE6-9CK, NACA4412 has the largest lift coefficient. When the incoming Mach number is greater than 0.4, the drag of RAE2822 airfoil increases faster than that of the other two airfoils, and the drag coefficient of NACA4412 airfoil increases less when Ma=0.4 or more, and the drag coefficient of the three airfoils increases faster.

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Therefore, when Ma= above 0.4, the lift-drag ratio growth rate of the three airfoils gradually slows down. NACA4412 airfoils have a higher lift-drag ratio under the conditions of various speeds in this paper, while NACA0012 and RAE6-9CK have similar lift-drag ratios.

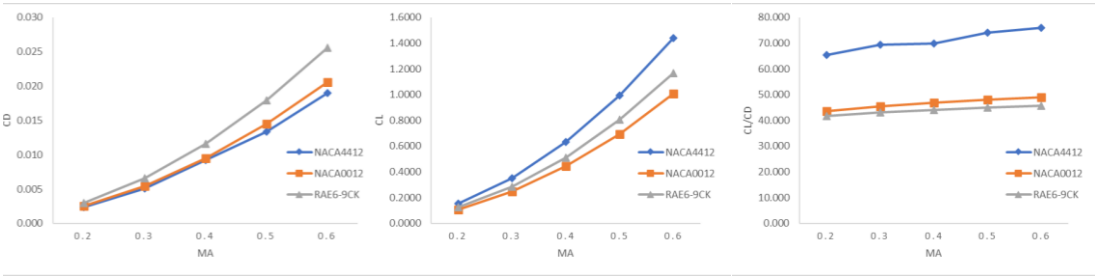


Figure 7: Airfoil lift coefficient, drag coefficient, and lift-drag ratio change curve with incoming flow velocity

4. Conclusion

In this paper, based on ANSYS Fluent, the aerodynamic characteristics of three airfoils under different incoming Mach number ground effects are studied and compared comprehensively. The effect of flight height on the aerodynamic characteristics of the NACA4412 airfoil under the condition of an inlet Mach number of 0.5 is analyzed in detail. In this paper, the research conclusion is as follows: different airfoil aerodynamic characteristics in ground effect under the influence of the variation law are different, can be seen in the three kinds of airfoil is NACA4412 in this paper, the ground effect environment lift coefficient and drag coefficient and lift-to-drag ratio is relatively better, therefore exists for high-speed ground effect aircraft airfoil design engineering significance.

In this study, several difficulties and challenges were encountered, including an insufficient in-depth understanding of CFD knowledge, limited airfoil data, and the inability of the simulation numerical methods to precisely simulate the flow field conditions. These issues would decelerate the research progress and, further, result in a considerable disparity between the simulation outcomes and the facts. Regarding the problem of an inadequate understanding of CFD, numerous CFD-related resources were collected on the internet and studied and applied. For the limited airfoil data issue, several airfoil databases were downloaded to obtain a considerable amount of airfoil data. Concerning the numerical simulation method, many papers were consulted to acquire the numerical simulation methods similar to the working conditions of this research.

In future work, the influence of airfoil parameters, including thickness and camber, on the aerodynamic characteristics of the airfoil under the ground effect will be deeply investigated, to better assist with the design of the wings of ground effect aircraft. With the accumulation of knowledge and the deepening of the research, better numerical simulation methods will also be sought to better simulate the fluid flow in this working condition.

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