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Research Status and Discussion of Front and Rear Wing Airfoil Design and Optimization of Racing Cars

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Abstract. Nowadays, aerodynamic theory is developing rapidly, the application field of the automobile industry is booming. Racing cars, as a product of the combination of the two, have developed a number of events around the world and have attracted widespread attention. The aerodynamic characteristics of the airfoil play a key role in the performance of the car. Based on four typical studies related to racing airfoil design and optimization, this paper analyzes their advantages and limitations, and summarizes the current status and advantages of cutting-edge research in this field. At present, the theoretical laws of lift, drag and their correlation coefficients have been basically mastered, and most of the work has been compared and analyzed around different airfoils, angles of attack and tracks. Some studies further put forward new calculation methods and optimization techniques to achieve refined processing of parameters. In view of the common limitations of existing research, the following improvement suggestions are put forward: clarify the key parameter settings, add wind tunnel tests, introduce mobile ground systems or mobile belts, and improve the application level of 3D modeling and Computational Fluid Dynamics (CFD) simulation technology.

Keywords: Racing airfoil, Computational Fluid Dynamics (CFD) simulation, aerodynamic characteristics.

1. Introduction

Aerodynamics research is a research focus in industrial fields such as aviation, marine, mechanical engineering, and automotive applications. In the field of transportation and energy utilization, aerodynamic research is the core starting point for reducing energy consumption, and it is also the core tool to deal with safety issues in high-speed and complex environments. Aerodynamic design often determines the ceiling of product performance. Airfoils play a very important role in aerodynamic applications, because the aerodynamic shape of an object has an important impact on its performance, so it is important to choose the right airfoil shape in the design [1]. Be advised that papers in a technically unsuitable form will be returned for retyping. After returned the manuscript must be appropriately modified.

In racing car design, vehicle engineers optimize the performance of the car with the goal of being fast based on safety, stability and specific race rules, and aerodynamics plays a very important role in this [2,3]. The advanced technologies developed for the purpose of the competition are not only

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constantly breaking through speed records, but also being applied to other aerodynamics-related industries. In previous studies, many researchers have proposed airfoils suitable for vehicle applications by studying the aerodynamic performance of different airfoils. Jian Zhou et al.'s research establishes the front and rear wing models of the racing car and concluded that the installation of the front and rear wings greatly improves the negative lift coefficient of the vehicle, thereby improving the handling stability of the vehicle [4]. Shamudra Dey et al. found that in the configuration of the study, the NACA 0012 airfoil can reduce drag and lift at the same time as a racing tail wing at +6° angle of attack, taking into account the efficiency and safety at high speeds, and is the optimal choice under the configuration in the study [5].Chen et al. analyzed the angle of attack, stall angle of attack, and the range of attack when the lift-drag ratio of NACA8516 the inverted tail is the largest , as well as the angle of attack of the maximum negative lift. It is found that the three-wing combination has better performance in terms of lift-drag ratio and stability. At the same time, it was also found that although the four-wing combination had greater negative lift, the drag increased and lift-drag ratio decreased [6].

Previous studies have generally compared specific airfoils or used simulation software to optimize airfoils for specific design goals, but few studies have systematically compared the advantages and disadvantages of active airfoils with theoretically optimized airfoils that have not yet been named and put into use. This study will compare different airfoils for the design of the front and rear wings of the racing car, and put forward suggestions for the use of different application scenarios, which can not only provide new ideas for the selection and optimization of the front and rear wings of the racing car in the future, but also provide certain reference significance for more accurate aerodynamic design and analysis in future related research.

2. Classical research conclusions and advantages

This study selects four classic studies as shown in Figure 1, which clearly and visually lists the research topics of the four studies, and all the analysis will focus on these studies below.

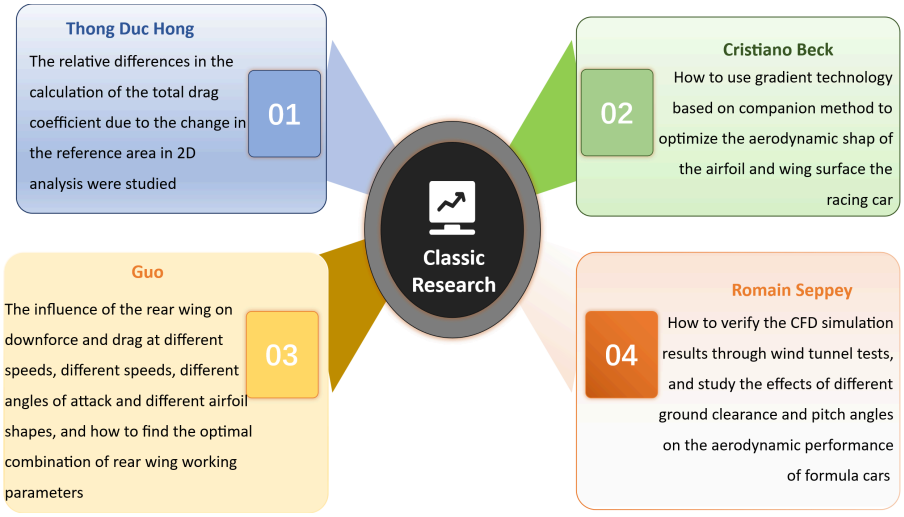


Figure 1. Summary of research limitations analysis and recommendations. (picture credit: original)

2.1. Thong Duc Hong's research

Thong Duc Hong et al. selected four different NACA airfoils and studied the relative differences in the calculation of the total drag coefficient caused by the change of reference area in two-

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dimensional analysis [7]. The experimental results show that all the resistance increases with the increase of velocity, while the corresponding coefficient decreases. The airfoil ratio and drag distribution have obvious effects on the drags component coefficient. The windward area method is not suitable for slender designs, and it is very important to accurately select the reference area for pressure and frictional resistance coefficients amplifies the output error. The advantage of this experiment is that a new method for calculating the resistance coefficient is innovatively proposed. Compared with multi-airfoil, multi-configuration, and wide range of research speed, it has important theoretical innovation value and engineering practice application value.

2.2. Cristiano Beck's research

Cristiano Beck et al. studied how to optimize the Cristite aerodynamic shape of the airfoil and wing surface of the racing car using gradient optimization technology based on the companion method to minimize drag while meeting the constraints of high lift, thereby improving the aerodynamic performance of the racing car [8]. Experiments show that the optimized reference airfoil with an obviously arced shape cannot achieve a high lift coefficient, and the drag coefficient of the reference airfoil is slightly lower than that of the optimized airfoil under a significantly higher lift coefficient under its maximum lift coefficient. It was also demonstrated that the companion method was suitable for designing racing airfoils. The advantages of this experiment are that the companion method is adopted, the computational efficiency is high, the high-fidelity RANS simulation is used, and the geometry parameters are flexible.

2.3. Guo's research

Guo et al. studied the influence of the rear wing on downforce and drag at different speeds, different angles of attack and different airfoil shapes, and how to find the optimal combination of rear wing working parameters [9]. It was concluded that the optimal working parameters of the rear wing of an F1 car should be the Drela AG03 (flat trailing edge) airfoil with a driving speed of 60 m/s and an angle of attack of about 20. The advantage of this study is that it is a multivariate system analysis and a comprehensive research dimension. Grid independent verification to ensure calculation reliability.And the simulation settings are close to the actual working conditions.

2.4. Romain Seppey's research

Romain Seppey et al. studied how to verify the Computational Fluid Dynamics (CFD) simulation results through wind tunnel experiments, and studied the effects of different ground clearance and pitch angles on the aerodynamic performance of formula cars [10].The experimental design and fabrication of the scaled wind tunnel model verify the trend validity of the CFD results, and conclude that ground clearance and pitch angle have a significant impact on the aerodynamic performance of the race car, and RA 3° is the optimal setting. The advantages of this research are that it adopts modular and adjustable design and has strong variable control ability. Multi-dimensional data collection was carried out to make the results more comprehensive. It is also compared with CFD simulation.

3. Limitations analysis and recommendations

As analyzed above, although the current research methods have matured and achieved certain research results, there are still shortcomings in the simulation process and data processing. In order

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to make the research results more practical, the limitations of these studies will be analyzed below and recommendations will be made in a targeted manner.

3.1. Study on the impact of reference area change

Although Thong Duc Hong et al. applied two methods to calculate the frictional resistance coefficient through ANSYS Fluent simulation software to study the relative difference in the calculation of the total resistance coefficient caused by the change of reference area, there is a problem that the influence of the actual area cannot be evaluated due to ignoring the influence of the surface roughness coefficient. It is recommended to carry out three-dimensional simulation on the basis of two-dimensional simulation to obtain more comprehensive experimental results and more complex aerodynamic phenomena. The study uses ideal gas in simulation, ignores non-ideal factors in actual flow, reduces the accuracy of the results in practical application, and it is recommended to use an incompressible flow model, or set the corresponding parameters such as density and viscosity.

3.2. Optimizing the aerodynamic shape of airfoil in combination with companion methods

Although Cristiano Beck et al. optimized the aerodynamic shape of the racing airfoil and wing by combining computational CFD and the Renault mean Navi-Stokes equation, there were problems that the optimization results did not consider the global optimum, and the geometric constraints were not strict enough to cause surface fluctuations. It is suggested that the wind tunnel test is closer to the real scene by using a mobile ground system or equipping the wind tunnel test section to simulate the impact of the ground effect. There is also the problem that there is no in-depth analysis of the stall characteristics of high angle of attack, and sudden separation and severe stall can be avoided by in-depth analysis of the stall characteristics of high angle of attack.

3.3. Simulate the aerodynamic performance of racing airfoils using CFD

Although Guo et al. numerically simulated the aerodynamic performance of the F1 car rear wing at different speeds, angles of attack and airfoils using commercial simulation software through computational CFD methods, there are limitations in the verification of grid independence, and there are differences in the tested airfoil scaling ratios, and the turbulence model selection lacks comparative verification. In this study, the ground effect, the dynamic effect in the real working condition and the vehicle interference are not considered, and all the results are numerical simulations, which lack experimental verification, so it is recommended to conduct wind tunnel tests to consider the flow interference of the vehicle in the actual situation.

3.4. Making models and experimenting in low-speed wind tunnels

Although Romain Seppey et al. conducted experimental tests in a low-speed wind tunnel by making a 1:4 scale model, studied the effects of different ground clearance and pitch angles on the aerodynamic performance of the racing car, and compared the experimental results with the CFD simulation results, there is a problem of insufficient geometric similarity of the simulation, and the aerodynamic similarity can be improved by designing a model that is more geometrically similar to that of a full-size racing car. The model in the study was manually processed to increase surface roughness, and the manual installation of hydrostatic holes led to measurement errors, and it was recommended to fabricate sensitive parts of the model with stronger materials or 3D print the

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precision parts with resin. It is recommended to build a 1:5 scale model to reduce the impact of the relative size of the car model relative to the test section on airflow, or use another metal to make a flat plate to reduce the curvature, and also add a support fixed plate.

4. Summary and discussion

The first two sections have analyzed 4 related studies, although these studies have made some progress and made some innovation in research methods, but still face many limitations. The corresponding suggestions for these limitations are also put forward in the previous article , which can be clearly reflected in Table 1.

Table 1. Summary of research limitations analysis and recommendations

	Thong Duc Hong	Cristiano Beck	Guo	Romain Seppey
Research Topic	Four airfoils were selected to study the relative differences in the calculation of the total drag coefficient due to the change of reference area in D analysis	How to use gradient optimization technology based on companion method to optimize the aerodynamic shap of the racing airfoil and wing surface to minimize the force under the premise of meeting the high lift constraints, so as to improve the aerodynamic performance of the racing car	The influence of the rear wing on downforce and drag at different speeds, different angles of attack and different airfoil shapes, and how to find the optimal combination of rear wing working parameters	How to verify the CFD simulation results through wind tunnel experiments, and study the effects of different ground clearance and pitch on the aerodynamic performance of formula cars
Limitations	1.Ignore the surface roughness factor. 2.Simulate only in 2D conditions. 3.Use ideal gas and ignore non-ideal factors in actual flow.	1.Geometric constraints that are not tight enough cause surface fluctuations 2.The ground effect is not taken into account 3.No in-depth analysis of the high angle of attack stall characteristics	1.There are differences in airfoil scaling tested. 2.The selection of turbulence model lacks comparative verification. 3.All results are numerical validation and lack experimental validation.	1.Insufficient analog geometry similarity. 2.The model is manually treated to increase surface roughness, and the manual installation of hydrostatic holes leads to measurement errors. 3.It cannot fully meet the requirements of the slimilarity of the Reynolds number of the real car.
Suggestions	1.Set the roughness in the model. 2.Three-dimensional simulation is carried out on the basis of two-dimensional simulation. 3.Use an incompressible flow model, or set the corresponding parameters such as density, viscosity, etc.	1.The actual construction of the car shows the addition of geometry that controls the smoothness of the curve. 2.The effects of ground effects are simulated by using a mobile ground system with moving belts in the wind tunnel test section. 3.In-depth analysis of the stall characteristics of high angles of attack to avoid sudden separation and violent stalling.	1.Unify the scaling of the model. 2.Conduct wind tunnel tests to consider the interference of vehicle flow in actual conditions.	1.Dessign a model that more geometrically similar to a full-size racing car. 2.Fabricate sensitive parts of the model using stronger materials, or 3D print precision parts with resin. 3.Build a 1:4 model,use another metal to make a flat plate to reduce bending, or add support to fix the flat plate.

In general, there are some common problems in the current cutting-edge research, such as: first, the use of an ideal experimental environment in simulation, ignoring some parameters to reduce the practicability of experimental results, for this problem, if only theoretical research is carried out, or to determine the general research direction, ignoring some irrelevant parameters can improve the

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computational efficiency. However, if it is for the study of practical application scenarios, it is necessary to reasonably set the relevant parameters or conduct wind tunnel experiments to enhance the experimental verifiability. Second, ignoring the ground effect, for this problem, there have been many studies on the design and optimization of mobile ground systems in recent years, and the application of this system can effectively solve this problem. Finally, due to the difficulty of 3D modeling and simulation, many studies are still stuck in 2D simulation, so it is very necessary to improve 3D modeling and simulation technology.

5. Conclusion

This study summarizes and analyzes four studies on the design and optimization of the front and rear wing airfoils of racing cars in recent years, which shows that the current research has basically grasped the theoretical laws of lift resistance and its correlation coefficient, and its influence on the aerodynamic performance of racing cars. At the same time, the comparative study of multi-airfoil, multi-angle of attack range and multi-track makes the research results more accurate and more practical. In addition, current research often explores new calculation methods and optimization techniques in simulation numerical simulations, and constantly updates accurate experimental parameters, which can be extended to other aerodynamic research, which has strong practical and innovative significance.

However, these studies also generally have some limitations, and on this basis, this study puts forward corresponding improvement suggestions. First, set important parameters and increase wind tunnel tests. second, using a mobile ground system or using a mobile belt to simulate the effects of ground effects; Third, improve 3D modeling and simulation technology. This study summarizes the existing airfoil design and optimization related research, and future research can refer to this study to make important parameters more accurate, optimize key experimental systems, improve the use ability of key technologies, broaden the application scope of experimental results, and refine the application scenarios of airfoils, so as to promote the development of airfoil-related aerodynamic research in the field of racing.

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