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Advancements and Innovations in Racing Car Aerodynamics: Cutting-Edge Techniques in Drag Reduction and Downforce Management

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Abstract. Racing aerodynamics is a core research area of modern racing engineering. It reduces air resistance and increases downforce by optimizing airflow management, thereby enhancing the speed, stability and maneuverability of the racing car. In recent years, Computational Fluid Dynamics (CFD) and wind tunnel experimental technology have been widely used in racing aerodynamic research, helping teams in events such as F1, Le Mans and Formula E to optimize the team streamline design and the angles of the front and rear spoiler panels to achieve the best balance between straights and curves. In addition, the application of active aerodynamic systems (such as F1's variable damping system DRS) and closed wheel design in the team further optimizes the final layout and improves the performance of the car. This study reviews the development of racing aerodynamics, analyzes the latest technologies in drag reduction and downforce management, and explores the potential application of artificial intelligence (AI optimization) in aerodynamic optimization. In the future, AI-driven intelligent aerodynamic adjustment and adaptive aerodynamic structure will become an important direction of racing aerodynamic research to improve the role of racing cars under different models and environmental conditions.

Keywords: Racing aerodynamics, CFD, Wind tunnel experiments, AI optimization

1. Introduction

Racing car aerodynamics is one of the core research directions of modern motorsports engineering, which reduces air resistance and improves downforce by optimizing airflow management to enhance the speed, stability and handling of racing cars [1]. In the development of motorsports, aerodynamics' importance has become increasingly prominent, especially in Formula One (F1), Le Mans, and Formula E, where aerodynamic optimization has become one of the key factors in deciding the winner [1]. In recent years, many breakthroughs have been made in the research of racing car aerodynamics, and F1 teams have widely used Computational Fluid Dynamics (CFD) technology to analyze the fluidity of racing cars, so as to find the best balance between straights and corners by optimizing the design of body streamlines and adjusting the angles of front and rear spoilers [2]. Active aerodynamic systems (such as F1's DRS Variable Drag System) have further advanced the development of race car aerodynamics, enabling the cars to reduce drag and improve

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overtaking ability in specific situations [3]. At the same time, endurance cars (such as the LMP1 and Hypercar) have adopted closed wheels and more efficient diffusers to reduce turbulence and optimize airflow distribution to minimize drag and increase downforce.

Against this background, this paper will review the development of racing car aerodynamics through literature and case studies, analyze the impact of aerodynamics on racing car performance, and discuss the current optimization techniques, especially the latest research progress in reducing drag and managing downforce. Also, it will combine Computational Fluid Dynamics (CFD) and wind tunnel experimental techniques to explore the future development trend of racing car aerodynamics, such as AI-driven intelligent aerodynamic adjustment, in order to further enhance the competitiveness of racing cars.

2. Overview of the development and role of aerodynamics in motorsports

The development of racing car aerodynamics has accompanied the evolution of motorsports itself, from the initial reliance on mechanical performance to today's high dependence on aerodynamic optimization, and the study of aerodynamics has become an indispensable part of racing car design. In the early days, aerodynamic effects were hardly considered in the design of racing cars, which mainly relied on engine power and lightweight structures to increase speed. However, as the speed of racing cars continued to increase, air resistance and vehicle stability problems gradually appeared, prompting engineers to explore how to use airflow to improve racing performance.

In the 1960s, the concept of aerodynamics made its way into race car design, with the Lotus team pioneering the use of a wing structure in F1, where the angle of the front and rear spoilers was adjusted to increase downforce and improve cornering grip [4]. This technology allowed cars to go faster through corners and dramatically changed the racing landscape. In the 1970s, the ground effect became an essential breakthrough in racing aerodynamics, and the Lotus 79 was designed with side skirts and chassis to optimize airflow and create strong downforce, making the car more stable at high speeds [5]. However, since excessive downforce can lead to dangerous situations, for example, the 1982 F1 accident caused by uncontrolled ground effects, the FIA imposed strict limits on aerodynamic design.

In the 21st century, aerodynamic technology has become more mature, and CFD and wind tunnel testing are widely used in F1 and other racing series to optimize the design of race car streamlines [6]. Modern race car design focuses not only on increasing downforce, but also on reducing aerodynamic drag and improving fuel economy, with F1's DRS (Variable Drag System) allowing the car to reduce the angle of the rear wing on straightaways, thus reducing aerodynamic drag and increasing top speed. Le Mans endurance cars (LMP1, Hypercar), on the other hand, use technologies such as closed wheel covers and active airflow control to balance speed and stability over long races. Overall, the development of aerodynamics makes racing faster and safer and continues to promote the innovation of racing technology, which has become one of the key factors in determining victory or defeat in modern racing competitions.

3. Basics of racing aerodynamics

3.1. Key aerodynamic parameters

The optimization of racing car aerodynamics depends on a series of key parameters, which determine the vehicle's stability, grip and top speed at high speeds [7]. Air resistance (drag) is the main factor affecting the speed of a racing car. It is generated by the combination of body shape,

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surface friction and wake turbulence, and is usually measured by the drag coefficient CD. One of the goals of racing car design is to reduce air resistance in order to minimize power loss and increase straight-line speed. For example, Formula 1 and Le Mans 1 (LMP1) cars are widely used with streamlined bodies and closed wheel covers to reduce aerodynamic drag.

Downforce is another key factor, which creates negative lift through aerodynamic design to bring the car closer to the track as it travels, improving the tyre grip. Increasing downforce enhances the car’s stability in corners, allowing it to take corners faster, but too much downforce also creates additional air resistance, so a balance needs to be found between the two. The coefficient of lift (CL) measures the amount of lift or downforce generated by a car, and race car engineers usually want CL to be negative to ensure that downforce outweighs lift. For example, the front and rear spoilers and chassis diffusers of Formula 1 cars are designed to optimize downforce, along with variable aerodynamic devices such as DRS, which reduce drag in straight lines and increase grip in corners. Together, these aerodynamic parameters determine the performance of a racing car, directly affecting its speed, stability and handling.

3.2. Application of CFD and wind tunnel experiments in racing car aerodynamics research

CFD and wind tunnel experiments are the two fundamental tools in modern racing car aerodynamics research, working together to optimize airflow design throughout the development process. CFD utilizes numerical simulations to predict airflow around the car, allowing engineers to evaluate the impact of various aerodynamic components during the design phase. Formula 1 teams, such as Red Bull Racing, rely heavily on CFD to enhance vehicle performance and refine aerodynamic efficiency [7]. Formula 1 teams widely use CFD for race car development, such as Red Bull Racing, which uses CFD analysis to improve the design of its side boxes to optimize airflow guidance and improve overall aerodynamic efficiency. The CFD is more flexible and cost-effective than traditional solid model testing, allowing engineers to test multiple aerodynamic scenarios quickly and iteratively on a computer.

CFD is not perfect. The airflow variations in a real racing car are highly complex, and relying solely on CFD simulation may lead to errors. Therefore, wind tunnel experiments are still crucial for aerodynamic research of racing cars. Wind tunnel tests are usually conducted with a 60% scale-down model to validate CFD calculations and accurately measure key parameters such as airflow distribution, downforce, drag, etc. [8] For example, the Mercedes-AMG F1 team uses wind tunnel experiments to optimize the car’s chassis diffuser to maximize ground effects and improve cornering stability. Modern race car development often combines CFD predictions with wind tunnel test validation to ensure that the aerodynamic design is accurate and that the car achieves optimal performance on the race track.

4. Analysis of vehicle drag reduction techniques

4.1. Analysis of resistance sources

Racing cars will be affected by air resistance when travelling at high speed, and the sources of resistance mainly include pressure resistance (Form Drag), friction resistance (Skin Friction Drag) and induced resistance (Induced Drag). These drag forces not only limit the car’s top speed but also affect fuel or energy consumption, so reducing air drag is one of the core objectives of aerodynamic optimization.

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Pressure drag is caused by squeezing the air in front of the car, resulting in a large pressure difference between the front and rear of the airflow, which creates drag. Streamlined design reduces this drag, and the nose and side boxes of F1 vehicles are designed to guide air smoothly through the bodywork, reducing the pressure difference. Frictional drag, on the other hand, is caused by the viscous interaction between the air and the surface of the car, and is closely related to the smoothness of the surface, the materials used, and the aerodynamic shape of the bodywork. Race cars often use low-friction coating materials and optimize airflow paths to reduce this drag. Induced drag comes primarily from the downforce generated by the race car, especially in the front and rear wing areas. As air flows over these components, the fluid vortices increase air turbulence and allow some energy to be lost to the air, creating additional drag. Therefore, modern racing cars minimize induced drag and improve aerodynamic efficiency by optimizing spoiler angles and diffuser design.

4.2. Racing vehicle optimization design

4.2.1. Body streamline optimization design

The streamlined design of a racing car body is crucial for reducing air resistance; a reasonably streamlined body can reduce air turbulence and improve aerodynamic efficiency. In high-speed racing cars (such as F1 and Le Mans), the optimization goal of the body shape is to minimize the front pressure resistance and, simultaneously, guide the air to pass through the body smoothly to reduce the impact of rear turbulence. Modern F1 cars use a tight sidebox design to improve aerodynamic efficiency by concentrating airflow from the side to the rear diffuser, while Red Bull's RB19 car achieves more efficient airflow management through a tighter sidebox shape, resulting in a better balance between downforce and straight-line speed in high-speed corners [7]. The Le Mans endurance car (LMP1/Hypercar) features a closed cockpit and streamlined fairing to reduce air resistance and improve fuel economy.

The design of the racing car's underbody is also a key part of streamlining optimization. The chassis of modern race cars often uses the ground effect principle, which allows air to accelerate underneath the car, creating a low-pressure region that increases downforce and reduces induced drag from rear vortices. The new rules for the F1 2022 season reinforce this feature, allowing cars to reduce air resistance while increasing ground adhesion, further optimizing aerodynamic performance.

4.2.2. Aerodynamic optimization of wheel and suspension systems

Wheel and suspension systems are one of the key areas for aerodynamic optimization of racing cars, especially open-wheel racing cars, like F1, which are more easily affected by air resistance and turbulence. Since wheels are rotating components, they strongly interfere with the air at high speeds, resulting in increased turbulence and thus increased air resistance. Optimizing the aerodynamics of the wheel area is therefore crucial, and the F1 teams have reduced turbulence generated by the wheels by installing wheel covers. For the 2022 season, the FIA reintroduced closed wheel covers to reduce the interference of the wheels with the surrounding air, resulting in a smoother overall airflow. Certain endurance cars, such as the Le Mans Hypercar, feature fully enclosed wheel covers to reduce air resistance further and optimize fuel efficiency over long races.

Aerodynamic optimization of the suspension is equally important. Modern F1 cars use push-rod or tie-rod suspension designs to reduce aerodynamic drag. For example, the front tie-rod suspension system introduced by Red Bull for the 2022 season optimizes airflow management in the underbody

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diffuser by varying the angle of the suspension arms, allowing airflow to pass more smoothly through the bodywork. In addition, some cars will have small deflectors added to the suspension components to minimize air interference and improve aerodynamic efficiency. Through these optimization measures, racing cars can not only reduce air resistance, but also improve aerodynamic stability, making the vehicle more controllable at high speeds.

4.3. Application of DRS in racing cars

DRS (Drag Reduction System) is a key technology used in modern racing cars to reduce air resistance and increase straight-line speed, first introduced by F1 in 2011 to increase overtaking opportunities. DRS reduces air resistance and increases a car's top speed by adjusting the angle of the car's rear wing to allow airflow through the rear of the car more smoothly [9]. In F1, when the distance between the car and the car in front is less than one second, the driver can activate DRS to increase straight-line speed and thus improve overtaking.

DRS works based on aerodynamic adjustments. When DRS is off, the car's rear wing is in its normal state, providing the car with more downforce and keeping it stable in the corner. In the DRS zone, however, the driver can turn it on and adjust the rear wing to reduce air resistance by up to 30 percent, thereby increasing straight-line speed. For example, on high-speed circuits such as Monza (the "Hall of Speed"), DRS can be used to give cars an extra 10-15 km/h speed advantage on the straights.

Not only in F1, but also in endurance racing (such as the Hypercar class in the WEC), variable aerodynamic systems are being used to adapt to different track conditions. The aerodynamic design of the Toyota GR010 Hybrid race car allows the rear wing to be adjusted on straights to reduce aerodynamic drag and improve energy efficiency. The application of these variable aerodynamic systems allows the car to optimize its aerodynamic performance in different track conditions, providing sufficient downforce in corners while reducing drag on straights, thus improving overall race performance. In the future, with the advancement of aerodynamic technology, DRS may be further combined with AI to achieve more intelligent aerodynamic adjustments to optimize the racing strategy of the car.

5. Conclusion

The advancements in racing car aerodynamics have significantly reshaped the landscape of motorsports, enhancing speed, stability, and overall performance. This research has demonstrated how the continuous development of aerodynamic techniques, such as CFD, wind tunnel testing, and active aerodynamic systems, has led to more efficient drag reduction and downforce management. From the early implementation of aerodynamic wings to modern variable drag reduction systems like DRS, these innovations have played a crucial role in refining vehicle handling and improving overtaking opportunities. Drag reduction techniques, including streamlined body designs, optimized diffuser placements, and closed-wheel configurations, have further minimized resistance while maintaining necessary downforce for cornering stability. Additionally, the integration of AI-driven aerodynamic adjustments marks a promising direction for the future, enabling real-time optimizations based on race conditions. The findings of this study emphasize that a balance between reducing air resistance and maximizing downforce is key to achieving superior race car performance.

This study has certain limitations, primarily due to its reliance on literature research. While it provides valuable theoretical insights, the lack of experimental validation limits its applicability to

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real-world scenarios. Future research should incorporate experimental methods alongside advanced technologies such as artificial intelligence and machine learning algorithms to enable real-time aerodynamic optimization and improve practical adaptability.

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