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Research on Fluid Mechanics Analysis and Optimization of Automobile Exterior Design

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Abstract. With the rapid development of the automotive industry and the increasing demand for environmental protection, automotive aerodynamics optimization has become a key approach to enhancing vehicle performance and reducing energy consumption. Based on the Computational Fluid Dynamics (CFD) method, this paper explores the relationship between the shape factors of automobiles and their fluid dynamics characteristics, with a focus on analyzing the influence of key factors such as the front styling, chassis structure, and rear wing design on aerodynamic drag and flow characteristics. Research shows that through the optimization of the front styling flow diversion, the flattening design of the chassis and the application of the adjustable rear wing system, the flow field distribution around the vehicle can be significantly improved and the aerodynamic drag coefficient can be reduced. This paper systematically constructs a research framework from local optimization to overall aerodynamic performance improvement. The research results can provide theoretical basis and practical reference for automotive styling design and aerodynamic performance optimization.

Keywords: Automotive aerodynamics, Fluid mechanics, Shape optimization, Chassis flow field, Adjustable rear wing

1. Introduction

The aerodynamic characteristics of automobiles are key factors influencing their fuel economy, handling stability and noise control. Research shows that when a vehicle is traveling at high speed, the fuel energy consumed by aerodynamic resistance accounts for more than 50% [1]. With increasingly strict environmental protection regulations in various countries and the rising demand for the driving range of electric vehicles, reducing aerodynamic resistance has become one of the core goals in automotive design. Traditional automotive design mainly relies on wind tunnel tests to verify aerodynamic performance, but this method is costly and time-consuming. In recent years, the rapid development of computational fluid dynamics technology has provided efficient and economical research methods for automotive aerodynamics studies [2]. Through numerical simulation, engineers can conduct in-depth analysis of the complex flow field structure around the vehicle, identify the sources of aerodynamic drag, and optimize the design for specific areas. This article will, from the perspective of fluid mechanics, systematically analyze the influence mechanisms of key factors such as the front styling, chassis structure, and rear wing design on the

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aerodynamic characteristics of automobiles, and explore the corresponding optimization strategies and methods, providing theoretical support for the aerodynamic design of modern automobiles.

2. The fundamental theories of automotive shape and fluid mechanics

2.1. Basic concepts of aerodynamics

Automotive aerodynamics mainly studies the laws of interaction between vehicles and the surrounding air, with a core focus on two major categories of issues: aerodynamic drag and aerodynamic lift. Aerodynamic drag is directly related to vehicle energy consumption, while aerodynamic lift affects the vehicle's handling stability and grounding performance. According to the different generation mechanisms, aerodynamic resistance can be classified into various components such as differential pressure resistance, frictional resistance and induced resistance. For typical passenger vehicles, pressure difference resistance accounts for the major part of the total resistance, mainly caused by the pressure difference between the front and rear resulting from airflow separation.

2.2. Influencing factors of automotive aerodynamic characteristics

The influence of various parts of a car's shape on its aerodynamic characteristics varies. Research shows that the front styling determines the impact area of the airflow ahead and the intake volume of the engine compartment. The chassis structure affects the airflow velocity and pressure distribution at the bottom. The rear styling dominates the scale and intensity of the vortex zone at the rear of the vehicle. The styling features of these areas jointly determine the aerodynamic performance of the entire vehicle [3].

3. Analysis and optimization of front styling factors

The front part of a car is the area where the oncoming airflow first comes into contact, and its styling features directly determine the development pattern of the global airflow. Poor front styling can lead to premature airflow separation, increase the area of the front positive pressure zone, and simultaneously trigger the generation of strong vortices, significantly increasing aerodynamic drag. Research shows that parameters such as the front bumper Angle radius, hood tilt Angle and front windshield Angle have a significant impact on the aerodynamic performance of the entire vehicle [4]. By optimizing the design of the air ducts on both sides of the front bumper, the airflow can more smoothly bypass the wheel covers, reducing the direct impact on the tires and thereby lowering the driving resistance. Another effective strategy is airflow management in the engine compartment. By precisely designing the opening area of the front air intake grille and the diversion path, the cooling airflow demand and the external flow field interference can be balanced [5].

4. Side profile and airflow management

The side profile of A car, especially the design of the rearview mirrors, A-pillars and waistlines, has a significant impact on the aerodynamic performance and airflow quality of the entire vehicle. As a protruding component, the rearview mirror generates complex vortex structures behind it. When these vortices strike the side Windows, they produce intense aerodynamic noise and increase local resistance [6]. By optimizing the shape of the rearview mirror, such as adopting a more streamlined

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cross-section and setting side air channels, the airflow can be directed more smoothly to the side of the vehicle, reducing the scale of vortices and energy loss.

The Angle at which the shape of the A-pillar area meets the front side window is another key factor. If the corner area of the A-pillar is too sharp, it will cause the airflow to separate here, generating A strong A-pillar vortex. This not only increases wind noise but also affects the cleanliness of the side window [7]. Modern automotive design effectively suppresses airflow separation and enhances the flow field quality in this area by increasing the fillet radius of the A-pillar, optimizing the transition relationship between the A-pillar and the side Windows, and even introducing small deflector plates for the A-pillar.

5. Flow field optimization of the chassis and bottom structure

The chassis area is a complex and crucial region in automotive aerodynamics research. Due to its complex structure (including components such as the suspension system, exhaust pipes, and fuel tank), it is prone to generating intense turbulent vortices and airflow separation. A key feature of the chassis flow field is the interaction between the lateral pressure gradient and the longitudinal flow velocity variation. When a vehicle is in motion, the airflow velocity at the bottom is usually lower than that at the top. According to Bernoulli's principle, this causes the bottom pressure to be higher than the top, generating aerodynamic lift [8]. The aerodynamic optimization of the chassis mainly focuses on two major directions: the flattening design and the deflector device. The flattened design makes the airflow at the bottom smoother by adding a chassis guard plate to cover the protruding mechanical parts. Research shows that a reasonable chassis guard plate can significantly reduce the aerodynamic drag coefficient of the entire vehicle [9]. For the bottom end of the vehicle's rear, the design of the Diffuser is particularly important. The diffuser reduces the airflow velocity and increases the pressure by gradually increasing the cross-sectional area, which helps to reduce the pressure difference resistance [10].

6. Rear wing and rear styling optimization strategy

The rear wing, as a key component influencing the flow field at the rear of a vehicle, mainly affects the aerodynamic performance of the entire vehicle by altering the airflow direction and pressure distribution. Its main function is to manage the air flow separation points on the rear window and luggage compartment lid, and control the formation and development of the rear vortex structure of the vehicle. An appropriate tail fin design can reduce the area of the wake zone and increase the base pressure, thereby significantly lowering aerodynamic drag [2]. Meanwhile, the rear wing generates downward aerodynamic pressure, increasing the load on the rear wheels and enhancing the vehicle's stability and cornering performance during high-speed driving. However, this increase in downforce often comes at the cost of increased resistance. Therefore, in the design, it is necessary to balance the relationship between resistance and downforce. To dynamically adapt to the aerodynamic requirements under different driving conditions, the adjustable rear wing system has emerged. The system optimizes aerodynamic characteristics under different vehicle speeds and driving scenarios by changing the Angle of the rear wing [11]. Apart from the specially designed rear wing, basic styling parameters such as the rear window Angle and the rear upturn Angle also have a significant impact on the rear flow field [12].

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7. Multi-objective optimization and future trends

Automotive aerodynamic design is essentially a multi-objective optimization problem, which requires seeking the optimal solution under multiple constraints such as low wind resistance, high stability, styling aesthetics, passenger space, and manufacturing processes. The combination of Computational fluid Dynamics (CFD) and optimization algorithms makes this complex multi-objective optimization possible. For instance, the optimization process based on parametric modeling and surrogate models (such as Kriging models and radial basis function models) can efficiently explore vast design Spaces, identify the Pareto optimal solution set, and provide designers with multiple performance-balanced solution options [13].

The future development trend will place greater emphasis on intelligence and system integration. On the one hand, machine learning and artificial intelligence technologies will be more deeply applied to flow field feature recognition and rapid performance prediction, thereby accelerating the optimization process. On the other hand, the aerodynamic design will be more closely coupled with the cooling system, braking system and the battery thermal management system of new energy vehicles. For instance, the layout of the bottom battery pack in an electric vehicle significantly affects the chassis flow field, and its heat dissipation requirements are directly related to airflow management. This demands an integrated collaborative design [14].

8. Conclusion

This paper systematically analyzes the aerodynamic effects of key factors such as the front styling, side styling, chassis structure and tail wing design, and explores the methods and development trends of multi-objective optimization. The following conclusions are drawn:

The optimization of the front styling should focus on the reasonable selection of the front window Angle and the front lift Angle. Through the design of the air duct and the active grille, a smooth transition and separation control of the airflow can be achieved. Side airflow management requires optimizing the shape of the rearview mirrors and the transition of the A-pillar to effectively control the generation of vortices, reduce aerodynamic noise and improve the quality of the flow field. The management of the chassis flow field requires the reduction of turbulent vortices through leveling design and deflector devices. Directional optimization measures such as the diversion flow deflector plate can effectively solve high-difficulty engineering problems such as local overheating. The rear wing and rear styling contribute the most to the vehicle's aerodynamic drag. Through the adjustable rear wing system (DRS) and flow field analysis, a significant drag reduction effect can be achieved.

Multi-objective collaborative optimization is the key to resolving the contradiction between aerodynamic performance and other design requirements, while intelligence and system integration will be the core directions for the future development of aerodynamics technology.

References

[1] Hucho, W. H. (2013). Aerodynamics of road vehicles: From fluid mechanics to vehicle engineering. Elsevier.
[2] Katz, J. (2006). Race car aerodynamics: Designing for speed (2nd ed.). Bentley Publishers.
[3] Barnard, R. H. (2019). Road vehicle aerodynamic design (4th ed.). MechAero Publishing.
[4] Wang, J., Li, X., & Chen, Y. (2020). Aerodynamic optimization of front-end styling for a passenger car based on CFD and orthogonal experiment. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 234(10), 2654-2667.
[5] Jiang, T., & Hu, S. (2022). Active grille shutter control for improved vehicle aerodynamics and fuel economy. IEEE Transactions on Vehicular Technology, 71(5), 4721-4732.

DOI: 10.54254/2755-2721/2026.MH30857

[6] Lee, J., & Park, S. (2021). Multi-objective aerodynamic optimization of a sedan body shape considering both drag and lift. Structural and Multidisciplinary Optimization, 64(2), 789-804.

[7] Ming, Z., & Li, Y. (2023). A review on active aerodynamics technology for passenger cars. International Journal of Automotive Technology, 24(1), 1-15.

[8] Wong, J. Y. (2008). Theory of ground vehicles (4th ed.). John Wiley & Sons.

[9] Song, L., & Yang, Z. (2021). Numerical investigation on the influence of underbody panels on the aerodynamic characteristics of a sedan vehicle. SAE Technical Paper No. 2021-01-0950.

[10] Zhang, H., Wang, C., & Zhou, D. (2022). Experimental and numerical study on the effect of rear diffuser angle on the aerodynamic performance of a fastback vehicle. Aerospace Science and Technology, 121, 107359.

[11] Li, W., & Guo, K. (2023). Aerodynamic optimization of a drag reduction system (DRS) in Formula SAE vehicles. Journal of Fluids Engineering, 145(3), 031401.

[12] Thacker, A., & Mclain, B. (2020). The influence of underbody roughness on the aerodynamics of a generic SUV (No. 2020-01-0679). SAE Technical Paper.

[13] Gillespie, T. D. (1992). Fundamentals of vehicle dynamics. SAE International.

[14] Gao, G., & Wang, J. (2023). Integrated design of aerodynamic and battery thermal management systems for electric vehicles. Energy, 263, 125689.