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Impact of Aerodynamic Design on Vehicle Performance and Vortex Wake Flow

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Abstract: This thesis examines vortex and wake formation mechanisms in automotive aerodynamics and their impact on vehicle performance, emphasizing strategies to mitigate adverse airflow effects through optimal design and computational techniques. It demonstrates that vortices and wake turbulence elevate drag, diminish fuel efficiency, and compromise high-speed vehicle stability. Streamlined body design, optimized rear-end shape, and underbody airflow management can effectively reduce wake turbulence and vortex intensity, enhancing aerodynamic performance. This paper also introduces a variety of computational techniques, including theoretical analysis, wind tunnel experiments and Computational Fluid Dynamics (CFD), and explores the application of these methods in the real-world design process. CFD simulation demonstrates its advantages in evaluating airflow characteristics and optimising design solutions, enabling engineers to carry out efficient iterative design. Future research directions include the application of active aerodynamic systems and the integration of intelligent design algorithms for more efficient airflow control and vehicle performance enhancement.

Keywords: Streamlining, Air resistance, Vortex, Fuel efficiency, Computational fluid dynamics (CFD).

1. Introduction

With the development of the automobile industry, aerodynamics has become an indispensable part of automobile design. Good aerodynamic characteristics not only improve the performance of a vehicle, but also reduce fuel consumption and emissions, thus having a positive impact on the environment and economy.[1]

Aerodynamics is an important branch of fluid mechanics, specialising in the study of the aerodynamic forces and their associated phenomena when an object moves in a gas. In the automotive industry, the study of aerodynamics began at the beginning of the 20th century when designers realised that the shape of a vehicle had a significant impact on its performance and efficiency. As automotive technology has evolved, the importance of aerodynamics has increased, especially in the context of increasing speed and performance requirements.

An in-depth study of automotive aerodynamics has several implications. For example, it can improve vehicle performance, enhance fuel efficiency, safety and security, and ride comfort. In this paper, the reduction of air resistance and the enhancement of fuel efficiency in improving vehicle performance are studied.

2. Minimizing aerodynamic drag in automotive design.

2.1. Streamlined design

Minimizing aerodynamic drag in automotive design: Rounded corners: The edges of the body and the front and rear of the vehicle should be designed with rounded corners to reduce the vibration and vortex generated by the air in these parts.

2.2. Body height and width

Low body height and width: Reducing the overall height of the vehicle helps reduce the area where airflow reaches the roof of the vehicle, thus reducing air resistance. Appropriate width: The width of the body should be reasonably designed to balance stability and resistance, avoiding the air resistance increased by over width.

2.3. Advanced materials and manufacturing processes

Use of lightweight materials: The use of aluminium alloy, carbon fiber and other lightweight materials can reduce the weight of the vehicle, making it easier to overcome air resistance when the vehicle is in motion.

Precision Manufacturing: High-precision manufacturing processes ensure smooth body surfaces and reduce friction when air flows over the surfaces.

2.4. Underbody airflow management

Flat bottom design: A flat bottom reduces the generation of vortices at the bottom, which helps air pass smoothly and reduces air resistance.

Air deflectors and diffusers: Adding air deflectors and diffusers to the underbody can direct airflow and reduce turbulence at the bottom and rear.

2.5. Rear design

Rear design: The rear of the vehicle should be designed in a narrow shape to reduce the drag generated by the tail flow. The slant back design is especially beneficial to reduce the airflow separation at the rear.

Spoiler application: Adding a spoiler to the rear of the vehicle can change the direction of the airflow, reduce turbulence and drag effects, and thus reduce drag.

2.6. Wheel and tyre design

Enclosed wheel covers: The use of enclosed wheel covers or designs that make the tyres fit more closely to the bodywork can reduce wheel-induced vortices and air drag.

Optimised tyre shape: Tyres should also be designed with air flow characteristics in mind to minimise drag caused by tyre rotation.

2.7. Active control of air flow

Adjustable Spoiler: Adjustable spoilers with electric or mechanical structures are used to optimise air flow by automatically adjusting their position according to the driving speed.

Active Aerodynamic System: Certain models are equipped with an active aerodynamic system that adjusts the shape of the vehicle and the direction of airflow according to the driving conditions.

2.8. Micro design details

Reflections and grooves: Tiny grooves or coatings on the surface of the bodywork can help airflow adhere better to the bodywork and reduce air resistance.

Thread and seam treatments: Optimising the design of seams in various parts of the bodywork ensures that air can flow through smoothly, rather than creating interference at the seams.

Summary: By using all of the above methods, automotive designers and engineers are able to effectively reduce aerodynamic drag, resulting in better acceleration and higher top speeds for the same power output, improved energy efficiency and fuel economy, as well as enhanced stability and handling at high speeds through optimised underbody pressure distribution.

3. Automotive aerodynamics enhances fuel efficiency.

3.1. Reduce air resistance

Streamlined design: A streamlined shape helps air flow more smoothly through the vehicle, reducing energy loss due to air resistance. When a vehicle is moving, air creates drag. Streamlined design effectively reduces this drag, allowing the vehicle to consume less fuel at the same speed.

Smooth surfaces: Smooth surfaces on the bodywork (e.g., the use of high-quality paint) can reduce the friction of air flowing over the surface, thus further reducing drag.

3.2. Optimising airflow management

Underbody design: By designing a flat underbody, vortices at the bottom can be reduced, and smooth airflow through the underbody area reduces the drag effect caused by airflow separation. This design significantly improves fuel economy at high speeds.

Rear end design: Optimised rear end design (e.g. slant-back rear end) reduces drag caused by airflow separation and wake turbulence. The proper shape of the rear helps to guide the airflow out smoothly, thus reducing drag.

3.3. Reducing the relationship between vehicle speed and wind resistance

Reduce the wind resistance coefficient when driving: The wind resistance coefficient (Cd value) is an important parameter to measure the aerodynamic performance of a vehicle. Reducing the Cd value through aerodynamic design can significantly reduce resistance and improve fuel efficiency even at the same speed. [2]

3.4. Reduction of vehicle speed in relation to wind resistance

Reduce the wind resistance coefficient when driving: Wind resistance coefficient (Cd value) is an important parameter to measure the aerodynamic performance of the vehicle. Reducing the Cd value through aerodynamic design can significantly reduce resistance and improve fuel efficiency even at the same speed.

3.5. Adoption of active aerodynamic technologies

Adjustable Spoiler: Some modern cars use adjustable spoilers that dynamically adjust their position according to the speed of the car in order to optimise the fit between the airflow and the body of the car, thus maintaining better aerodynamic performance at different speeds and helping to improve fuel efficiency.

Active Airflow Control System: In some high-end models, the Active Airflow Control System monitors and adjusts the wind resistance outside the vehicle in real time to ensure optimal aerodynamics in all driving conditions.

Summary: As vehicle speed increases, air resistance increases significantly, resulting in higher fuel consumption. By optimising vehicle design, such as adopting a streamlined body, reducing the surface area of the body and using aerodynamic kits, air resistance can be effectively reduced, resulting in reduced fuel consumption and improved fuel efficiency

4. Aerodynamic design methods

The calculation methods of automotive aerodynamics are mainly used to analyse and optimise the airflow characteristics of the vehicle when it is moving in the air, as well as to calculate aerodynamic forces such as air resistance and lift. The following are some commonly used automotive aerodynamic calculation methods[3]

4.1. Theoretical analysis method

Basic Fluid Dynamics Equation: Using the principles of basic fluid dynamics, the air resistance of a vehicle is estimated by calculating the pressure distribution and flow shape on the surface of an object. Bernoulli's equation: Under ideal fluid conditions, Bernoulli's equation is applied to calculate the pressure and velocity changes of fluids in different cross-sections.

4.2. Wind tunnel experiments

Model testing: A scaled-down model of a vehicle is made in a wind tunnel, and actual data are obtained by measuring the forces (e.g., air resistance, lift) exerted by the airflow on the model.

Data analysis: Recording and analysing flow characteristics using sensors and data acquisition systems, especially testing the model at different angles and speeds.

4.3. Computational Fluid Dynamics (CFD)

CFD simulation: 3D modelling of the car using CFD software (e.g. ANSYS Fluent, OpenFOAM, COMSOL, etc.) to simulate the flow behaviour of the airflow around the car.

Meshing: The model is divided into small cells (grids) and the flow characteristics within each cell are calculated.

Equation solving: Solve the Navier-Stokes equations to obtain the velocity and pressure fields.

Post-processing: Analysing the simulation results, such as flow lines, pressure distribution, vortex structures, etc., to evaluate the contour design and aerodynamic performance.

4.4. Proven empirical equations

Drag Coefficient Calculation: Calculate the air drag coefficient (Cd value) for vehicles of different shapes using known empirical formulas, e.g.:

$$C_d = \frac{F_d}{\frac{1}{2} \rho A V^2} \qquad (1)$$

Where (F_d) is the drag force, (\rho) is the air density, (A) is the windward area, and (V) is the vehicle speed. [4]

4.5. Dynamic simulation

In the realm of multi-body dynamics (MBD) analysis, the dynamic behavior of a moving vehicle is evaluated through MBD simulations, taking into account the influence of aerodynamic drag on velocity and handling stability. [5]

4.6. Optimisation algorithms

Genetic Algorithm: Use genetic algorithm or other optimisation techniques to find the best design through parameter optimisation to reduce air resistance.

Sensitivity Analysis: Analyses the effect of design parameters on aerodynamic performance to identify key parameters and optimise them.

Summary: These calculation methods can be used individually or in combination to obtain a more accurate and comprehensive aerodynamic analysis of the vehicle. As computing power increases and software technology develops, the combination of CFD and wind tunnel testing will be able to provide more effective solutions for optimising vehicle designs and improving their aerodynamic performance.

5. The role and influence of vortex wake in automotive aerodynamics

In automotive aerodynamics, vortices and wake are important concepts for understanding the effects of air flow on vehicle performance, stability, and fuel efficiency. A detailed description of vortex and wake will be examined in terms of the concept of vortex wake, the effect of vortex wake on air resistance, and improvements. [1]

5.1. Concept of vortex flow

Vortex is the phenomenon of rotating flow of a fluid due to the change of velocity in the flow. During the travelling of a vehicle, the airflow changes its shape around the vehicle, resulting in the formation of different types of vortices. These vortices have a significant effect on the aerodynamic characteristics of the entire vehicle.

Front vortices: When air flows towards the front of the car, vortices are created near the front of the car. These vortices cause local pressure changes that affect the way the air flows.

Tyre vortices: the rotation of the wheels also causes vortices in the surrounding air, especially at high speeds, and vortices around the tyres increase the overall air resistance.

5.2. Concept of wake turbulence

Tail flow is the irregular flow of air that forms as it passes over the rear of a vehicle. This flow usually manifests itself as a low-pressure region and creates a vortex area at the rear of the vehicle. Tail flow has a significant impact on the performance and stability of a vehicle.

Tail flow pattern: Tail flows are generated behind the vehicle's motion and usually appear as irregular vortex flows, the nature and strength of these flows can be influenced by the shape of the rear of the vehicle.

Characteristics of the wake stream: The wake stream will cause a negative pressure area, this negative pressure not only increases the air resistance, but also may have an impact on the subsequent moving vehicles, causing them to suffer additional drag.

5.3. Effects of vortices and wake turbulence on air resistance

Increased air resistance: Both front vortices and wake turbulence can increase the air resistance of a vehicle. In particular, wake turbulence reduces the air pressure behind the vehicle, causing more drag as the air is discharged.

Impact on fuel efficiency: Due to the increase in air resistance, the vehicle needs to use more energy to overcome this resistance, resulting in lower fuel efficiency.

Dynamic stability: the creation of wake turbulence negatively affects the dynamic stability of the vehicle under the influence of wind speed changes or other external factors, which may lead to a reduction in the vehicle's manoeuvrability.

5.4. Methods to reduce vortex and wake

Through reasonable design, vortex and wake can be effectively reduced, thus improving aerodynamic performance:

Streamlined design: Adopting a streamlined shape facilitates the smooth passage of air through the vehicle and reduces the formation of front vortices and wake flows.

Optimised rear end shape: Designing a vehicle with a sloping back or rounded rear end can effectively reduce the intensity of the wake and reduce the negative pressure area at the rear.

Wind deflectors and diffusers: Adding wind deflectors or diffusers to the rear of a vehicle can help control the direction of the wake flow and reduce drag caused by airflow separation.

Pneumatic outsourcing: Using pneumatic outsourcing technology to combine the body and chassis to improve airflow and reduce tail vortex.

5.5. Future research direction

As automotive aerodynamics research evolves, scientists and engineers will continue to optimise the management of vortices and wake turbulence to enhance the aerodynamic performance of vehicle designs. Future research is likely to focus on:

Advanced Computational Fluid Dynamics (CFD)techniques: using more advanced simulation software to predict software and analyse airflow behaviour to optimise design solutions.

New materials and manufacturing technologies: research into new materials and manufacturing processes for better streamlined design and detailing.

Active control systems: developing intelligent systems to adjust the shape of the vehicle body or the position of the components according to real-time wind speed and driving conditions to optimise air flow.[6]

6. Conclusion

This thesis provides an in depth analysis and discussion of the vortex and wake phenomena in automotive aerodynamics. Through the research on the mechanism of vortex and wake formation, the impact on vehicle performance, and the related design and calculation methods.By means of streamlined design, optimisation of the shape of the rear section, and improvement of underbody airflow management, the intensity of wake turbulence and the influence of vortices can be significantly reduced. These design improvements can not only effectively reduce the air resistance coefficient of the vehicle, but also improve the dynamic stability of the vehicle under various driving conditions. A combination of theoretical analysis, wind tunnel experiments and Computational Fluid Dynamics (CFD) provides engineers with a comprehensive set of tools to simulate and optimise the behaviour of vortices and wake turbulence, with CFD techniques in particular demonstrating the benefits of rapidly evaluating the airflow characteristics and associated aerodynamic performance during the design iteration process. Vortices and wake are central to understanding the airflow behaviour of a vehicle as it moves through the air. At high vehicle speeds, vortex formation and wake characteristics directly affect air resistance, vehicle stability, and fuel efficiency. Therefore, a reasonable grasp of these phenomena is crucial for optimising vehicle design.

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