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The Study on Development, Application and Performance Improvement of Active Rear Spoilers in Production Vehicles

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Abstract. The application of active aerodynamic systems within modern vehicles has seen a notable rise with the aim of tackling the disadvantages of fixed aerodynamic devices when facing with differing driving conditions. Active rear spoilers have gained considerable notice since they have the ability to automatically change their geometry parameter in response to instant driving data in various driving conditions with the function of improving the energy efficiency and vehicle handling. This paper firstly provides a review of the fundamental concepts of automotive aerodynamic, from basic principles such as drag, lift to flow separations. It also reviews the development process of rear wings, from early fixed ones to active rear wings, emphasizing the reason and benefit of this change. It points out the development of rear spoilers from fixed to active ones, emphasizing the logic and benefit from it. In addition, this paper demonstrates new control strategies that better combined with other vehicle systems, allowing a more unified measures to manage vehicle dynamics through active rear wings. The application of active rear wings with the functions of optimizing the energy efficiency and enhancing handling stability on production cars will be also discussed.

Keywords: Active aerodynamic, vehicle aerodynamic, vehicle handling, rear wings

1. Introduction

Automotive aerodynamics plays a crucial role in determining the performance, efficiency, and stability of production vehicles. With the development of automobile engineering, the speed of vehicles has increases significantly therefore aerodynamic drag has become a critical factor that considerably affects the energy consumption of vehicles. In addition, it is well known that aerodynamic lift force can reduce grip and affect vehicle handling, particularly in high-speed situations. Therefore, optimizing automotive aerodynamic performance has become an essential aspect of modern vehicle design.

Traditionally, influenced by motorsport, high-performance vehicles usually use passive aerodynamic devices such as fixed rear spoilers in order to improve the airflow around the vehicle. They are designed with specific angle of attack to generate specific amount of downforce. However, their fixed geometry limits their effectiveness under varying driving conditions and lead to the generate of drag force, which has a negative effect on the energy efficiency of vehicles. As a result,

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passive aerodynamic rear spoilers are considerably unable to achieve optimal performance across all operating conditions of vehicles.

In order to deal with these problems, active aerodynamic systems have been developed and gradually applied in production vehicles. Among various types of active aerodynamic technologies, active rear spoilers have gained significant attention due to their ability to automatically adjust their position or attack angle in response to specific driving conditions, with the change of speed, acceleration or braking. In general, active rear spoilers can reduce aerodynamic drag during cruising while enhancing downforce in order to offer improvement on vehicle handling and stability when required.

This paper presents a review of the development, applications and the performance improvement of active rear spoilers in production vehicles and particularly focus on their ability in drag reduction and handling enhancement. The advantages, challenges, and future trends of active rear wings will also be discussed to provide a comprehensive understanding of their significance in modern automotive engineering.

2. Fundamentals of automotive aerodynamics

Automotive aerodynamics mainly focus on the interaction between vehicle and the surrounding airflow. In general, forces mainly applied on vehicles include drag forces and lift forces. It is believed that these two forces have a significantly influence on the vehicle dynamic performance, including energy efficiency and driving stability. Understanding the fundamental concepts is crucial for comprehend the effectiveness and functions of active rear spoilers.

2.1. Aerodynamic drag

The vehicle's air resistance is composed of about 80 % pressure drag, less than 10 % cooling drag due to internal flow through the engine room, less than 10 % drag due to undercover and undercarriage, and less than 5 % surface friction drag [1]. It is believed that pressure drag comes from the pressure difference between the front section and rear section of the vehicle, causing by flow separation. Flow separation is a phenomenon that the airflow cannot stick to the vehicles' surface smoothly especially in areas that are curved and separate from the surface of the vehicles. The friction drag is a result from viscous shear stresses along the vehicle surface that generates from the boundary layer close to the vehicle body.

The intensity of aerodynamic drag is usually expressed by using the value of drag coefficient (Cd) in automotive aerodynamic. It has been proved the drag coefficient mainly depends on the shape of the vehicle body. A lower drag coefficient value always represents a lower air resistance and better aerodynamic efficiency. In modern production vehicles, manufactures utilize various measures to lower the drag coefficient, including the application of active rear wings. Studies have proved that the reduction of drag plays a critical role in enhancing the energy efficiency and optimizing the wind noise performance of both internal combustion engine vehicles and electric vehicles.

2.2. Lift and downforce

It is well-known that the direction of lift force is vertical with the direction of vehicle motion. The positive lift could significantly reduce the forces between the tires and the road surfaces, therefore decreasing traction especially at high-speed operating conditions, which might cause dangerous

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situations in some extreme driving conditions [2]. As a counter measure, aerodynamic devices are designed to generate downforce, which is negative lift force. It has been confirmed that downforce can make the tires press more tightly against the road surfaces to gain more grip for vehicles in order to enhance the handling and stability. Among various aerodynamic components, rear aerodynamic devices, especially rear wings, have a significant impact on optimizing the airflow and generating considerable downforce to reduce the negative effects caused by lift forces.

3. Development of rear spoilers

The development of rear aerodynamic devices has experienced an important transformation over the past decades. It has developed from merely simple and fixed parts to more complex and intricate systems. At the beginning, the designs were relatively simple and didn't have much complexity. But with the increasing demand for better aerodynamic efficiency, especially in the racing industry, there was a strong drive towards innovation. It gradually had an impact from the high-speed racing sector and is starting to influence the design concepts of production vehicles as well. For active rear spoilers on modern production vehicles, considering the rear wing setup, it was presented the downforce can be increased by 80% for the maximum performance mode with adequate mounting setting, which enabled it to move off the wing into a more advantageous position. In the braking mode, the downforce increased to 62%, and the drag increased by 16% to improve the braking performance [3].

3.1. Early development of spoilers

In early stages of automotive aerodynamic design, rear spoilers were mostly non-adjustable devices with fixed geometries. They were mainly designed for modifying airflow separation at the rear end section of vehicle. Studies and application in reality have proved that the lift coefficient increases gradually as the angle of attack increases within the range of -6°to 18°, and the drag coefficient increases simultaneously [4]. Fixed spoilers were primarily adopted in race car and high-performance vehicles due to their simplicity, low cost, effectiveness and well reliability.

However, the efficiency of fixed spoilers is limited by their inability to adapt to various driving conditions. This led to the development of active rear wings in racing cars, such as the Chaparral 2E, and their gradual adoption in production vehicles, including the famous Bugatti Veyron 16.4 Super Sport, not only had a rear wing acting as an airbrake but also had a spoiler placed beneath it, which enabled an even greater increase of the drag coefficient equal to 0.347 while braking [2]. Although these designs have a significant advantage compared with fixed spoilers, their functionality was still relatively limited due to their simple control strategies and ways of operation were usually associated with only one or a few parameters without considering more sophisticated driving conditions and dynamic factors.

3.2. Modern electronically controlled systems

It is believed that active rear spoilers have developed towards a more integrated and sophisticated direction due to the development of modern automotive electronics and control techniques. Contemporary active aerodynamic systems are generally controlled by electronic control units (ECU), which process real-time vehicle data, including speed, braking input, and driving conditions.

These systems are capable of adjusting the position and angle of the spoiler in a continuous manner, with the objective of optimizing aerodynamic performance. For instance, the spoiler can be

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deployed at high speeds in order to generate downforce to push the tires towards the road surfaces to enhance vehicle stability, retracted during steady cruising to reduce the drag for better energy efficiency and rapidly flip with a specific angle during braking to function as an air brake to improve the braking performance. It has been demonstrated that incorporating these multifunctional capabilities can significantly boost both efficiency and safety.

4. Operating principles and control mechanisms

Active rear spoilers have the ability to change their geometry parameters in real time according to the current driving condition, including position and angle. Compared with passive aerodynamic devices, their functionality highly relies on integrated control systems, mainly by electronic control units (ECU). With the capability of processing vehicle data in real time and specific control strategies, active rear wings are able to make contribution to production vehicles in different driving conditions.

4.1. Speed-based control

Vehicle speed is one of the most important parameters in the control of active aerodynamic system and that is the reason why speed-based deployment of the active rear wings stands as a commonly adopted control strategy. With this method that commonly utilized in production vehicles, the spoiler deployed in specific morphometric right after the vehicle attains a preset speed to optimize the drag and downforce for a better handling at high-speed conditions. If the vehicle's speed falls beneath the preset speed, the spoiler will automatically retract itself in order to avoid the unnecessarily generation of drag for better energy efficiency. On some production vehicles with asymmetric aerodynamic components, similar control strategy has shown that active aerodynamics system is able to utilize the aerodynamic drag of the left and right wings to obtain the expected additional yaw torque by changing the angle of attack of the active air surface [5]. This approach is crafted to keep a balance between aerodynamic efficiency and handling performance of production vehicles.

4.2. Angle adjustment and optimization

It is believed that wing configuration parameters (including wing mounting height, and angle on the flow structures around the vehicle and wing) have a significant influence on the vehicle's aerodynamic characteristics [6]. Modern active aerodynamic systems are capable of adjusting the angle of attack of the rear wings with the hydraulic or electronic actuation components. Compared with traditional fixed rear wings, this design undoubtedly providing a greater flexibility of adaptation to various driving conditions and find a balance between minimizing air resistance for energy efficiency during cruising, and producing enough downforce to improve grip and stability at high-speed conditions or during extreme maneuvers. This deals with the inherent trade-off between drag reduction and downforce generation.

4.3. Integration with vehicle systems

Modern active aerodynamic systems are usually integrated and linkage with other vehicle systems such as braking systems and electronic stability control (ESC). This integration mainly relies on the muti-system integrated controller to achieve. It is believed that using the control strategy of the active pneumatic system in multi-system integrated controller exhibits better performance in handling stability of production vehicles [5]. Research have shown that a multi-actuation model

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predictive controller can track a vehicle's yaw motion and stabilize its lateral dynamics effectively [4]. Integration of aerodynamic systems with other vehicles systems are capable of exchanging real-time data, allowing for a coordinated response among different vehicle components or systems. This coordination is of great importance because it greatly improves the vehicle's performance. It is believed that this is able to pursue all aerodynamic components including active rear wings function together smoothly to attain the best outcomes in control and responsiveness across various driving conditions. For instance, during emergency braking, the spoiler can be deployed in a specific manner aggressively and intended to increase aerodynamic resistance, thus enhancing the vehicle's ability to stop and shorten the braking distance.

5. Aerodynamic performance analysis

To analyze the performance and effectiveness of active rear wings, computational fluid dynamics (CFD) simulations is a tool that is capable of helping designers to comprehend the interaction between active rear wings to the surroundings. A large amount of research, including computational fluid dynamics simulations and wind tunnel tests, has shown their ability to exert a substantial influence in these areas. CFD simulations are capable of simulating the genuine airflow patterns around the spoiler, helping optimize its design and make sure its effectiveness.

5.1. Drag reduction

Active rear wings on production vehicles have the ability to reduce the drag. Retracting the active rear spoilers ensures the vehicle's surfaces remains smooth and unobstructed, which substantially reduces the disruption of airflow and the separation behind the vehicles. This reduction is especially beneficial for electric vehicles since manufactures usually pay quantities of attention to extend the range. Researches have demonstrated that the optimization of spoiler configurations can result in quantifiable decreases in drag coefficient (Cd). This reduction leads to a better energy performance and better aerodynamic efficiency on production vehicles.

5.2. Downforce generation

The active rear wings have the ability to alter the airflow and utilize the pressure difference between the upper and lower surface to generate downforce, which is capable of optimizing the vehicles' handling and stability. The efficiency of the generation of downforce is related to the shape, size and the angle of spoilers. Research have shown that the rotation of a small movable aerodynamic element placed in the right place on the car body can generate forces typically obtained by many times larger aerodynamic elements open new possibilities for the use of active systems of vehicle aerodynamic damping. Such small and effective elements are ideal for aerodynamic actuators in automatic systems of production vehicle [7]. This notion implies that through adequate design and placement of these small active rear wings, it is possible to gain considerable aerodynamic advantages without having to resort to large, cumbersome aerodynamic structures which increase the weight and drag of the vehicle.

5.3. Balance between drag and stability

It is believed that a primary element in the design of active rear wings is the management of the trade-off between the drag reduction and the stability enhancement. The deployment of a rear spoiler increases downforce but add additional drag force simultaneously. Improving the structure design of

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spoilers' surface and pylons with the help of CFD simulations will make contribution in finding a better balance between drag and stability. It has been proved that top-mounted rear wing could avoid flow detachment caused by disturbances from the pylons [8]. It is also worth noting that active rear wing systems are capable of address this trade-off by dynamically adjusting their geometry configuration to achieve optimal performance under varying driving conditions.

6. Applications in production vehicles

The use of active rear spoilers is no longer confined to a select segment of high-performance vehicles. The application of these systems has undergone a gradual expansion in line with the increasing prominence of aerodynamic efficiency as a design consideration. Research have demonstrated that the aerodynamic forces generated by active rear wings that tilt the car body inwards during cornering and successfully suppress vibrations to improve the road-holding capability and ride comfort [9].

6.1. High-performance vehicles

In high-performance vehicles, active rear spoilers are employed to enhance stability at high speeds. The spoiler of modern high-performance vehicles is capable of preventing the flow from staying attached to the smooth rear end of the car body and directed it towards the wing [10]. It is evident that these systems are frequently calibrated to deploy with considerable force, prioritizing downforce and handling performance.

6.2. Electric vehicles

In contradistinction, electric vehicles tend to prioritize efficiency. In such cases, the spoiler is often kept retracted during steady driving to reduce drag, while still providing additional stability when required. It is particularly noteworthy that the impact of aerodynamic drag on range renders such systems especially valuable.

7. Conclusion

Active rear spoilers present a practical solution to the limitations associated with fixed rear spoilers. They are able to make adequate adjustments which enable the improvement of aerodynamic efficiency on production vehicles. Active rear spoilers are capable of offering a greater degree of flexibility. It improves the ability of adaptation to various driving conditions of production vehicle to reduce the drag for better energy efficiency and enhance downforce for better handling stability in separate conditions. Moreover, the active aerodynamic system's ability to react to real-time conditions makes it possible for production vehicles to interconnect with other intelligent systems.

Despite of these advantages, there are still challenges present for active rear wings on production vehicles. It has been demonstrated that the integration of actuators and control systems of active rear wings can increase both costs as well as complexity for manufactures, which might cause a potential increase in budget and maintenance processes. Additionally, the reliability of the active rear wings in severe conditions such as snow or water is a considerable problem. Exposure towards severe weather conditions can result in malfunctions or a decline in performance over time, putting the system's stability and longevity at risk. Moreover, in order to achieve a smooth integration with other vehicle systems, careful calibration as well as control design is crucial, which requires enough technical reserve and experience for manufactures.

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Overall, active rear spoilers represent an important direction in the evolution of automotive aerodynamics, particularly with the function of increasing aerodynamic efficiency and performance of production vehicles. It is believed that development and future trend in active rear spoiler systems are possibly to focus on improving control precision and system integration. It is foreseeable that advances in sensing and data processing will allow for more refined and responsive aerodynamic adjustments.

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