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A Study on Active Aerodynamic Components in Modern High-Performance Vehicles

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Abstract. With the increasingly strict global regulations on energy conservation and emission reduction and consumers' pursuit of high-performance car handling, active aerodynamic components have become a critical component in modern car design. The design of traditional fixed aerodynamic components only achieves optimal aerodynamic performance under specific operating conditions. When the vehicle is in multiple operating scenarios, its aerodynamic performance significantly decreases in accordance with actual needs, making it difficult to balance the overall performance of the vehicle. Active technology adjusts components such as the tail wing, spoiler, air dam, and air intake grille in real-time to adapt to different driving conditions, dynamically optimizing low wind resistance during high-speed cruising, high downforce in bends, and emergency braking performance. This paper systematically analyzes its technical principles and simulation methods, combines typical application cases such as F1 and supercars, and looks forward to the future development trend of intelligence, so as to provide a reference for the development of automobile active aerodynamics.

Keywords: Active aerodynamics, active tail wing, active spoiler

1. Introduction

In recent years, the rapid development of the automobile industry has made consumers increasingly demanding for vehicle performance, fuel economy and safety. To address these challenges, active aerodynamics packages have gradually become one of the key technologies in modern automotive design. Traditional aerodynamic designs rely primarily on stationary packages, which balance pressure and windage by optimising the shape of the body, but their performance is often optimal only under certain conditions. However, the emergence of active aerodynamics technology enables the vehicle to dynamically adjust the aerodynamic characteristics under different driving conditions by adjusting the posture or shape of external parts of the vehicle body in real time, so as to significantly improve the comprehensive performance of the vehicle.

The core of active aerodynamics is its dynamic response. When the vehicle is cruise at high speed, the active aerodynamics package can improve the extreme speed or reduce the fuel consumption by reducing the wind resistance; When the vehicle is in motion mode or emergency braking, the controllability and safety of the vehicle can be improved by increasing the downward pressure or auxiliary braking. The application of this technology is not only widely used in the high-performance sports car or racing field, but also gradually infiltrated into the commercial vehicle and general passenger vehicle markets, becoming one of the key technologies to enhance vehicle competitiveness.

From a technological point of view, the prototype of active aerodynamics dates back to motorsport in the middle of the 20th century. Early designs were simple, such as manually adjustable tail fins or air intakes. With advances in electronic control technology, modern active aerodynamics systems have been highly automated and can monitor parameters such as speed, acceleration and crosswind in real time via sensors and quickly adjust aerodynamic packages with the help of actuators. For example, the DRS (Drag Reduction System) system in F1 helps the driver overtake by reducing drag in straight sections by adjusting the angle of the tail; Super sports cars such as Bugatti Veyron and Porsche 918 reduce braking distances considerably by converting air drag into braking force through automatically raising tail fins during emergency braking.

In addition, active aerodynamics is continually expanding its application scenarios. For example, models such as McLaren W1 and Zenvo TSR-S have further optimised the downforce distribution in curves through the design of the tail fin tilting towards the bend centre, improving the over-bend limit.

Despite the advantages of active aerodynamics, their large-scale application faces challenges such as increased system complexity, increased reliability requirements, and increased maintenance difficulty. In the future, with further developments in materials science, control algorithms and sensor technology, active aerodynamics packages are expected to be available in a wider range of models and inject new impetus into the sustainable development of the automotive industry.

The purpose of this paper is to systematically review the application of modern high performance vehicle active aerodynamics, focus on analyzing its technical principles and typical cases in drag reduction, increase of downward pressure, auxiliary braking, etc., and discuss its future development trend, so as to provide reference for research and practice in relevant fields.

2. Introduction to active aerodynamic systems

2.1. Active aerodynamics

Active aerodynamics is a technology that optimizes the aerodynamic performance of a vehicle by adjusting external components such as the tail wing, spoiler, and air intake in real-time. Unlike traditional fixed designs, it can dynamically adjust based on driving conditions such as vehicle speed, steering, and braking, achieving the best balance between reducing wind resistance, enhancing downforce, or improving stability.

The development of active aerodynamics relies on the advancement of sensors, electronic control systems, and lightweight materials. In the future, with the deepening of intelligent technology, it will become a key means to improve vehicle efficiency, safety, and handling.

2.2. Theoretical basis of aerodynamics in automotive design

2.2.1. Air resistance

Calculation formula for air resistance:

$$F_d = \frac{1}{2} \rho v^2 C_d A \tag{1}$$

F_d refers to air resistance (unit: N); ρ is the air density (unit: $\mathrm{kg/m^3}$); v is the velocity of the object relative to air (unit: m/s); C_d is the resistance coefficient; A is the windward area of the object in (unit: m^2).

This formula shows that the air drag is proportional to the square of the velocity, the air density, the drag coefficient and the windward area. In automobile design, reducing the windage coefficient and reducing the windward area is the key to reduce the air resistance and improve the fuel efficiency. Conversely, for the purposes of deceleration, the deceleration capability of the body components to the vehicle can be increased by increasing the drag coefficient and increasing the windward area.

2.2.2. Pneumatic lift force

Expression of Bernoulli equation:

$$p + \frac{1}{2}\rho v^2 + \rho g h = C \tag{2}$$

p is the pressure at a certain point in the fluid (unit: Pa), representing the pressure energy per unit volume of the fluid; ρ is the density of the fluid (unit: $\mathrm{kg/m^3}$); v is the flow velocity of the fluid at that point (unit: m/s); g is the acceleration due to gravity, usually taken as 9.8 m/s; h is the height of the point relative to a reference plane (unit: m).

The Bernoulli equation states that in the stable flow of an ideal fluid, as the fluid velocity increases, the pressure decreases. For a streamlined vehicle, the shape of the upper surface of the vehicle is more curved than the lower surface, and the distance of air flowing through the upper part of the vehicle is greater than the distance of air flowing through the bottom of the vehicle, so the speed of air flowing through the upper part of the vehicle is higher than the speed of air flowing through the bottom. Based on Bernoulli's equation, a low pressure zone is formed on the upper surface of the vehicle and a high pressure zone is formed on the lower surface. The differential pressure between the upper and lower surfaces causes the aerodynamic lift. In a car design, the lift can be counteracted by increasing the chassis air flow rate to create downward pressure. The downward force can enhance the stability and performance of the vehicle [1].

2.2.3. Coanda effect

The Coanda effect is due to the entrainment of ambient fluid by in-phase primary jets. When there is an approximate surface, a low pressure region is formed around the jet due to entrainment of the ambient fluid between the jet and the surface, causing the jet to deflect towards the wall due to the pressure gradient near the surface (suction force balance).

The experimental results show that when the Coanda jet flows along a continuous and curved surface, it can entrain up to 20 times its volume of fluid. By designing the body surface to guide airflow attachment, the Coanda effect is used to guide airflow to a specific area to increase downforce or reduce wind resistance.

2.2.4. Venturi effect

Venturi effect refers to the low pressure near the fluid flowing at high speed, resulting in adsorption. For automotive design applications, the airflow is accelerated through the underbody venturi channel design to create downpressure.

3. Vehicle aerodynamic optimization simulation analysis method

3.1. Aerodynamic six-part force

In the aerodynamic analysis of the vehicle or model, the origin of the coordinate system is set as the intersection of the vehicle wheelbase centerline and the wheelbase centerline on the ground. The axial direction of the coordinate system is defined as: the x-axis points forward to the rear of the vehicle, the y-axis points forward to the right side of the vehicle, and the z-axis points forward to the top of the vehicle.

The air forces acting on the vehicle body include aerodynamic drag, aerodynamic lateral force, aerodynamic lift, and the moment around the center of mass generated by its positional relationship with the center of mass: roll moment around the x-axis, pitch moment around the y-axis, yaw moment around the z-axis.

3.2. Model establishment

The 3D modeling software is used to model and restore the vehicle appearance and simplify the structure in combination with the basic theory of aerodynamics. For example, to improve computational convergence and save computational resources, the interior spaces of the passenger compartment, engine, fuel tank, and exhaust system can be enclosed to exclude these areas from the computational domain. For the small parts in the model that have little impact on the airflow, such as bolts, buckles, gaskets, wire harnesses, etc., the model can be removed. Reasonable boundary conditions are set by CFD analysis method. For the computational domain, the height of the flow field is equal to or greater than 7 times the vehicle height, the width on both sides of the vehicle is equal to or greater than 7 times the vehicle width, the front of the vehicle head is equal to or greater than 3 times the vehicle length, and the rear of the vehicle is equal to or greater than 8 times the vehicle length. The side and top surfaces of the computational domain are sliding walls or symmetric boundary conditions, and the ground behind the vehicle and the whole vehicle are non-slip walls.

3.3. Generate calculation node

The simulation model shall realize the real simulation of each key local flow field, and the size and scale parameters of the calculation node can be reasonably determined according to the actual conditions such as calculation resources. Small gaps between the engine compartment internals or the connection of the tire to the ground often lead to large aspect ratio and highly distorted meshes, which need to be densified to avoid CFD solver divergence or to obtain inaccurate results. Numerical model mesh discretization is performed on the model and mesh independence analysis is performed to determine the optimal mesh number for the finite element model. The airflow near the car body will generate velocity gradient under the influence of car body, and multi-level body grid densification area is set to optimize the simulation.

3.4. Model solver

The solution software based on N-S equation can perform steady state or transient solution calculation. The solution software based on N-S equation can perform steady state or transient solution calculation. However, due to the extremely high computational cost of directly solving the N-S equation (DNS), CFD usually adopts RANS or LES methods. The solver based on the LBM method does not need to solve the N-S equation directly. For low Reynolds number laminar flow or weak turbulence, the details of the flow field can be directly captured through fine grid simulation. For high Reynolds number and strong turbulence, the large eddy simulation (LES) framework can be introduced to optimize the computational efficiency, or the separated eddy simulation (DES) method based on LBM can be adopted to adapt different accurations in the near-wall region and the far-field respectively.

3.5. Evaluation and design

Obtaining a velocity nephogram, a pressure coefficient nephogram, a velocity vector nephogram, a streamline diagram, a surface shear force nephogram, an isosurface nephogram and a windage coefficient accumulation curve, and proposing a vehicle area where the aerodynamic performance can be improved by adding a pneumatic additional device. The aerodynamic attachment is designed and several design schemes are proposed. The design scheme with the minimum aerodynamic drag coefficient is obtained through fluid simulation analysis again.

4. Application of active aerodynamics components in modern vehicles

The use of active aerodynamics in modern vehicle design is very extensive, and its main application scenarios can be divided into drag reduction, increased downforce, auxiliary braking, optimal comfort, etc. Structurally, common design ideas include variable tail fins (DRS) or movable spoilers, active air grilles (AGS), underflow management, active air skirts (AAS), etc.

4.1. Drag reduction design

4.1.1. Drag Reduction System (DRS)

The DRS system enables drivers to adjust the rear wing Settings to reduce drag and increase the top speed on the straight. Under conditions where weather and regulations permit, activating DRS can bring about a speed increase of approximately 10-20km/h to Formula One cars. DRS allows the rear wing to rotate at specific stages of the race, thereby reducing drag and downforce and thus increasing speed. It is used on the straight because at this time the car needs a higher speed and downforce is not necessary.

From the Fig. 1, the DRS system operates through a pneumatic piston that moves an arm, causing the flaps to rotate around a fixed axis. The DRS actuator is located beside the bracket and its shape is as efficient as possible to avoid generating additional resistance [2].

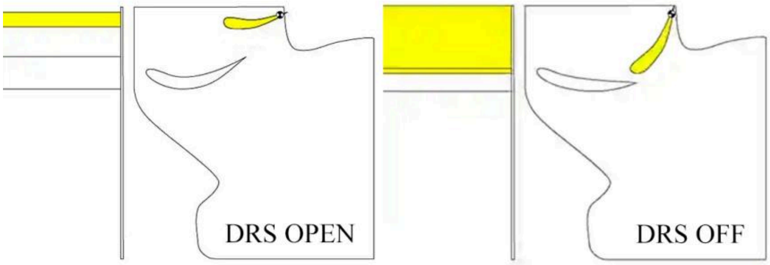

Figure 1. Section view of tail fin shape when DRS is opened and closed

From the Fig. 2, we can see that the left car keeps the DRS closed compared to the right car (which keeps DRS open). The upwind area of the racing tail is significantly reduced:

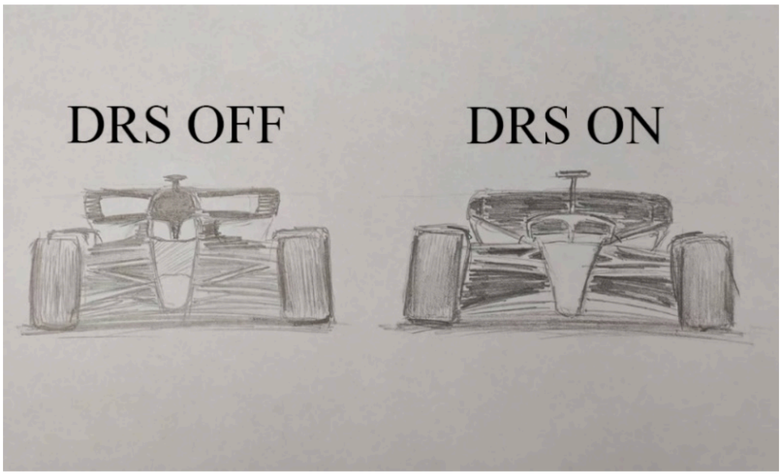

Figure 2. Impact of opening and closing of DRS system on vehicle resistance

4.1.2. Aerodynamics Lamborghini Active (ALA) syetem

The ALA system actively adjusts the aerodynamic load based on dynamic conditions to achieve high or low pressure or low drag. The electronic drive motor opens or closes the active flaps on the front separator and engine hood to guide the airflow at the front and rear in the best way.

The front splitter is equipped with two motor-driven flaps. In the off state, the airflow will flow simultaneously above and below the splitter, thereby increasing the load on the front wheels. When the flaps are opened, the upward airflow is directed to the underside of the vehicle, reducing both downforce and air resistance [3].

Air ducts with small flaps are provided at two positions where the hollow bracket connects to the surrounding vehicle body. The rear wing is also a hollow structure, with holes on its lower surface for guiding the air flowing through each bracket into the rear wing. Each flap is controlled by an inertial platform computer, which is connected to the vehicle's powertrain and chassis systems. When the flaps are opened, air flows upward along the support, passes through the tail fin cavity, and is then discharged from the lower side of the tail fin to eliminate the pressure difference between the upper and lower surfaces of the tail fin, thereby significantly reducing downforce and air resistance [3].

4.1.3. Ferrari dynamic air flow control system

The aerodynamic components of the Ferrari SF90 Stradale include closed flaps. The suspension wing at the tail end of the engine hood contains a moving part with a wedge-shaped front. The moving part is called a closed flap and has been patented. When traveling in urban areas or at the maximum speed, the two components are aligned and suspended on the engine hood. The moving part with a wedge-shaped front serves as an effective deflector for the fixed part, allowing the airflow to pass through the upper and lower parts of the closed flaps.

The aerodynamic components of the Ferrari chassis include actively adjustable bottom spoilers. The actively adjustable bottom deflector plate dynamically controls the extension or Angle change of the chassis deflector plates, enabling the vehicle to retract the deflector plates when traveling in a straight line and reducing the air resistance under the vehicle.

4.1.4. Active Grille Shutter (AGS) system

Under high-speed driving conditions, AGS is an effective means to reduce wind resistance. It can dynamically and precisely adjust the opening degree of the air intake grille based on the real-time driving status of the vehicle, thereby significantly reducing the coefficient of wind resistance. This effect is achieved by ingeniously creating a stagnant pressure in front of the baffle, thereby forcing air to flow around the vehicle rather than through the cooling components and the engine compartment [4]. This design ingeniously utilizes aerodynamic principles, ensuring the vehicle's normal heat dissipation requirements while significantly enhancing its energy efficiency during high-speed driving. Depending on different vehicle models, specific cooling requirements, and the differences in the number and design of the air flap system, when in the closed state, the overall resistance encountered by the vehicle can be reduced by 3% to 8% [5].

As shown in the Fig. 3, the drag coefficient (cd) of the 911 Turbo varies with different aerodynamic Settings. The left picture shows the open state of the air intake deflector plate, and the right picture shows the closed state of the air intake deflector plate. The most efficient configuration with a minimum cd value of 0.33 is achieved by closing the front air intake deflector and retracting the front and rear spoilers. The continuously adjustable air intake deflector enables the vehicle to travel with lower resistance, thereby reducing fuel consumption. The air deflectors are located inside the air inlets on both sides of the front bumper. They are continuously adjustable and can be used to regulate the air flow through the radiator. When the vehicle speed reaches 70 Km/h, the air deflector will be closed, which reduces consumption for daily driving operations and improves fuel economy.

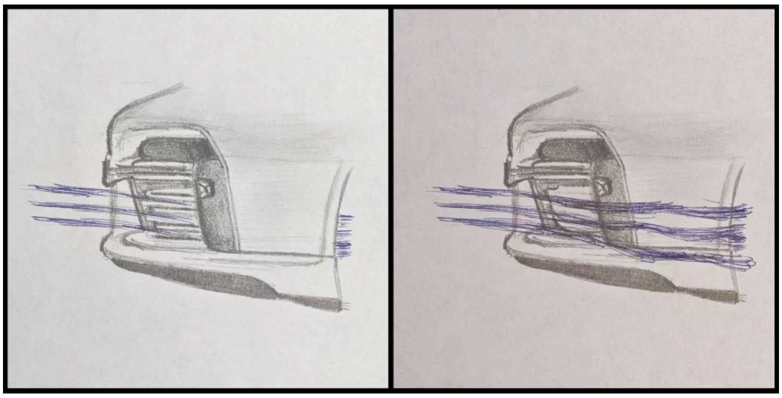

Figure 3. Porsche dynamically adjusts the opening degree of the air intake grille

4.2. Increase downforce design

4.2.1. Mclaren active long tail

The McLaren Active Long Tail can extend backward by 300 millimeters in racing mode, which can transform the entire rear of the vehicle into an aerodynamic diffuser similar to that of an F1 racing car. Combined with a carefully tuned active spoiler system, the vehicle can generate up to 1,000 kilograms of downforce in extreme conditions, which is five times that in road mode. Bring unparalleled track performance. The deformation function not only changes the appearance of the car but also expands the working area of the diffuser.

As shown in the Fig. 4, the road mode is at the top and the racing mode is at the bottom. It can be clearly seen that the tail fin connected by the carbon fiber bracket (racing mode) extends backward.

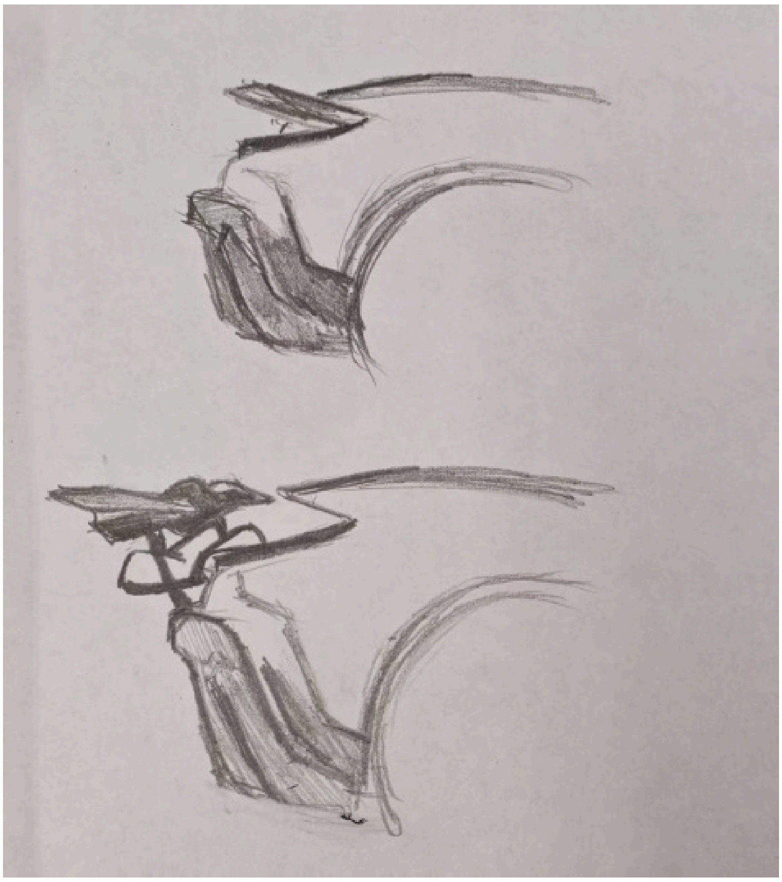

Figure 4. Road mode (part 1) and racing mode (part 2)

4.2.2. Active front spoiler

Compared with other Porsche sports cars that are not equipped with the Porsche Active Aerodynamics (PAA) system, the active front spoiler of the Porsche 911 Turbo has a significantly larger effective aerodynamic area, enabling it to flexibly perform extension and retraction within a short period of time and under low pressure conditions. The spoiler is made of special flexible plastic material and consists of three independent sections. Each section can be inflated independently and precisely controlled in coordination with the synchronous operation of external actuators.

This spoiler is equipped with three adjustable configurations: In the basic configuration, the spoiler is fully retracted and fixed to meet the daily driving requirements; When in the speed configuration, only the external areas on both sides extend, which can effectively reduce the lift of the front axle and enhance the stability during high-speed driving. In the performance configuration, the three-segment structure is fully unfolded, providing high-performance aerodynamic effects while generating maximum downforce on the front axle, meeting the demands of intense driving scenarios. In addition, the control unit and the air compressor are installed on one side of the luggage compartment. The compact pneumatic module design increases the luggage compartment volume by 3 liters. The variable front spoiler lip can also increase the approach Angle, providing convenience for daily parking and passing over speed bumps and other scenarios.

4.2.3. Tiltable rear wing

The Zenvo TSR-S adopts innovative aerodynamic technology to enhance stability and high-speed turning, namely the active multi-axis radial wing, whose lateral Angle of attack can vary by up to 20 degrees.

As shown in the Fig. 5, the white arrows represent the centrifugal force of the vehicle, the yellow arrows represent the reactive force exerted by the air on the rear wing, the red arrows represent the force exerted by the rear wing on the vehicle perpendicularly to the ground, the blue arrows represent the force exerted by the rear wing on the vehicle horizontally to the ground, and the green arrows represent the force exerted by the vehicle on the tires during a curve. When a vehicle turns right to enter a curve, the centrifugal force will cause a significant increase in the pressure on the outer wheels, while the pressure on the inner tires will decrease. At this point, the inclined tail fin is subjected to the counterforce of the air, not only generating a downward pressure perpendicular to the ground but also forming a lateral component force horizontal to the ground (pointing towards the inner side of the curve). This lateral component force can partially counteract the influence of centrifugal force, thereby balancing the difference in the normal pressure distribution between the inner and outer wheels and enhancing the vehicle's stability when cornering.

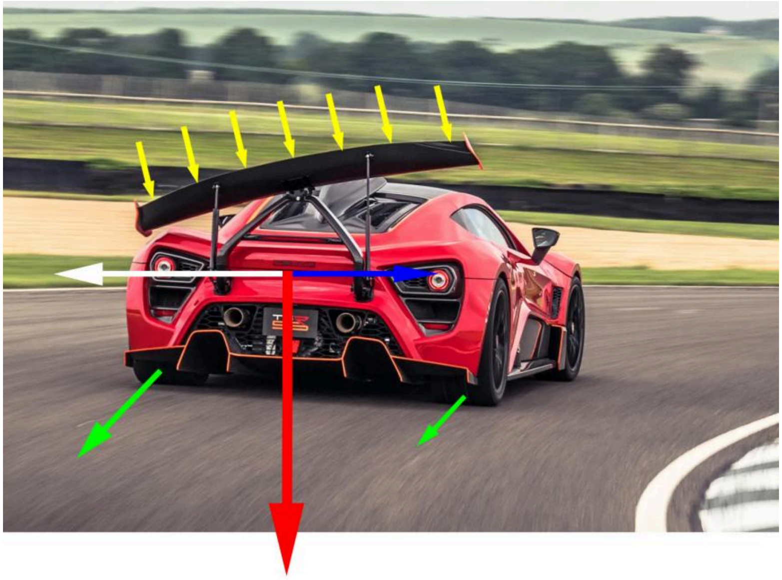

Figure 5. The force on Zenvo TSR-S in the curve

4.2.4. Active air dam

An air dam is an anti-flow device installed under the front bumper or in the air intake area of a car. Its main function is to reduce the airflow under the vehicle through real-time physical deformation (extension/retraction/flipping/Angle adjustment), thereby reducing the lift generated during high-speed driving, lowering the tendency of the vehicle's front lift, and improving driving stability and handling, as well as enhancing steering accuracy. Common active air dams are connected by mechanical structures with hard plastic parts or by using flexible materials. The main body of an air dam can be classified into one-section type, segmented type, separated type, etc. For its control algorithm, it has evolved from the early linear control based on vehicle speed to multi-parameter coupled control.

4.2.5. Portable rear air diffuser

The movable rear diffuser is mainly installed under the rear anti-collision beam of the vehicle, and its mechanical principle is based on the Bernoulli principle in fluid mechanics. Diffusers are typically composed of a drive, a transmission shaft, and multiple adjustable guide vanes or telescopic panels, which are driven by motors, hydraulic actuators, or stepper motors to change the blade Angle or overall height. When the vehicle is in motion, the motor main control chip receives parameters such as vehicle speed and wheel Angle. Under high-speed or curved conditions, by increasing the Angle between the inclined surface of the diffuser and the ground, the expansion of the airflow under the vehicle is accelerated, and the Venturi effect is utilized to enhance the low-pressure area and increase the downforce.

For instance, the PAA system enables the active rear diffuser to unfold during high-speed braking or cornering, thereby increasing the braking force on the rear axle. The Xiaomi SU7 Ultra supports 0° and 32° adaptive adjustment, balancing the low wind resistance during daily driving with the high and low pressure during high-speed and intense driving.

4.3. The design of auxiliary braking

Bugatti Veyron is a model of active adjustment technology for contemporary automotive aerodynamic characteristics. This model is not only equipped with a movable aerodynamic kit, but also innovatively achieves full-dimensional active control of the vehicle's posture. In addition to moving aerodynamic components, it can also change the position of its body relative to the road surface, and has adjustable ground clearance and adjustable body tilt Angle. This is regarded as the first intelligent aerodynamic management system in the history of automotive design [6].

Under high-speed conditions (exceeding 200 kilometers per hour), the aerodynamic braking function of this system is activated as shown in Fig. 6. When the driver triggers the braking command, the Active Rear Spoiler integrated at the rear of the vehicle can rise rapidly within 0.4 seconds and precisely lock to the optimal Angle of attack position of 55°, enhancing braking performance by significantly increasing the aerodynamic drag coefficient (Cd value). Firstly, it can increase the downforce on the rear axle, thereby improving the distribution of braking force between the front and rear axles. Secondly, it will increase air resistance, just like the situation when an airplane lands. At high speeds, the air brake activated by braking pressure can produce a deceleration of up to 0.6G.

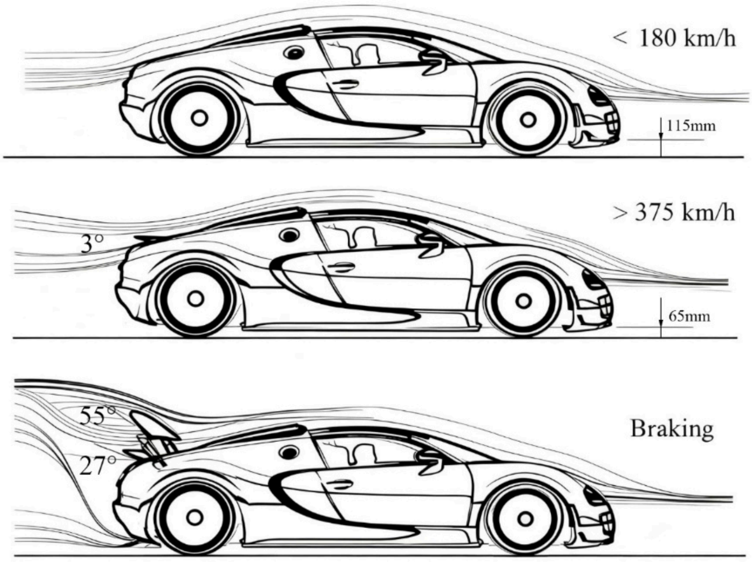

Figure 6. The relationship between the rear wing Angle and airflow at different speeds

This design is widely applied. For example, the active spoiler of the Ferrari 296 SPECIALE A has four height adjustments. The spoiler is fully closed in the low wind resistance mode and can switch to a high downforce setting for a short time when facing emergency braking. When braking, the motors on both sides of the Zenvo TSR-S simultaneously raise the Angle of attack of the rear wing to the maximum, generating additional drag and acting as an air brake.

Some car manufacturers no longer focus on controlling the rear wing but instead concentrate their core efforts on precisely controlling the lift of the vehicle body. They installed several wing plates on the upper part of the vehicle body with the aim of creating an asymmetrical lift and drag effect. The specific operation is to set up small wing plate structures in the areas where the vehicle body is inclined upward. These structures can effectively promote the occurrence of airflow separation, thereby destroying the lift effect and increasing air resistance. For instance, the Pagani Huayra features two hinged carbon fiber plates at the front and rear as spoilers. When emergency braking occurs, the four spoilers rise, forcing the airflow to separate, reducing the vehicle's lift and generating additional downforce to enhance tire grip and provide considerable air resistance to assist in deceleration [7]. Meanwhile, the electronic control unit can track air flow velocity, yaw state, steering Angle, throttle position, accelerator pedal and other signals, continuously adjusting downforce and air resistance to ensure the vehicle maximizes the utilization of aerodynamics.

5. Expectation

The possible research directions of future active aerodynamics technology are as follows:

Intelligent aerodynamics, through the efforts of domestic and foreign experts and scholars in recent years, has been increasingly widely applied in fields such as rapid flow field prediction, transition prediction, turbulence modeling, and multi-source data fusion, achieving remarkable research results [8]. In the future, machine learning technologies related to artificial intelligence can be utilized to carry out intelligent pneumatic design. By using artificial intelligence technology to replace expert experience, the role of "human in the loop" can be weakened, and the level of intelligent pneumatic design can be enhanced [9]. In addition, shape memory alloys can be used to replace traditional mechanical structures, achieving an active deformation structure without motor drive. In addition, these components can be used for energy absorption. For instance, Wu Zhipeng et al [10]. innovatively developed a multi-level buffer energy-absorbing structure, using intelligent alloy materials with elastic properties as the core energy-absorbing components. This design takes advantage of the high energy density and flexible deformation characteristics of special metal wires to achieve progressive energy dissipation during vehicle collisions, effectively controlling the peak impact force. If shape memory alloys are used as materials for some easily damaged mechanical structures, these components can not only serve as active aerodynamic devices but also act as energy-absorbing structures during impacts. Even after minor damage, they can be thermally restored, thereby enhancing vehicle safety and economy. Intelligent adaptive pneumatic accessories are also a research direction with great development prospects. The traditional design method of the tail wing system cannot take into account the nonlinear relationship between the input and output of the control system. The adaptive fuzzy control tail wing calculates the optimal tail wing attack Angle corresponding to each vehicle speed based on the vehicle speed and acceleration [11, 12]. Its strong robustness is sufficient to tolerate sensor noise and aerodynamic parameter uncertainties. If an adaptive fuzzy control tail wing system is adopted, the Angle of attack can be adaptively adjusted when encountering complex flow field conditions such as crosswinds, vehicle wake interference, and single-sided wall contact. Furthermore, as it does not require the establishment of an accurate flow field-tail coupling mathematical model, it empirically maps complex working conditions through a fuzzy rule base, reducing the reliance on precise fluid dynamics modeling. By integrating deep learning to study the aerodynamic characteristics of different vehicle models in real time, it is expected that through artificial intelligence, membership functions and rule weights for fuzzy control can be automatically generated based on parameters such as vehicle speed, center of gravity, and drag coefficient, achieving intelligent cross-model application adaptation for multiple vehicle models.

6. Summary

The active aerodynamics technology of modern high-performance vehicles has expanded from the development in the field of racing to a core means to enhance the overall performance of civilian vehicles. Dynamic response capability is the core of active aerodynamics. By adjusting the Angle of attack and area of the airflow of components such as the rear wing, spoiler, air dam, and air intake grille in real time through the electronic control system, the local airflow path of the vehicle is precisely optimized. Reduce wind resistance during high-speed cruising and increase downforce when cornering or braking.

This article lists some key application scenarios and innovative designs: In terms of drag reduction design, the DRS system of F1 can increase the vehicle speed by 10-20km/h by adjusting the Angle of the rear wing. Lamborghini's ALA system optimizes airflow by controlling flaps with motors. The closed flaps and the actively adjustable bottom deflector of the Ferrari SF90 Stradale work together to reduce drag. The AGS system of the Porsche 911 Turbo can reduce wind resistance by 3% to 8%. In terms of increasing downforce, the downforce of the McLaren Active Long Tail can reach five times that of the road mode, with a maximum of 1,000 kilograms. The tiltable tail fin of Zenvo TSR-S generates a lateral component force by 20° lateral deflection to counteract the centrifugal force. The three-stage flexible spoiler of Porsche's PAA system regulates the downforce of the front axle in different modes. The movable rear diffuser (such as the 0° and 32° adaptive adjustment on the Xiaomi SU7 Ultra) utilizes the Venturi effect to enhance downforce. In the field of auxiliary braking, the active spoiler of Bugatti Veyron rises to 55° within 0.4 seconds, generating a deceleration of 0.6G. The Ferrari 296 SPECIALE A and Zenvo TSR-S also have corresponding spoiler adjustment designs; The Pagani Huayra uses fenders to create asymmetrical lift and drag to assist braking.

Although active aerodynamic design has obvious technical advantages over other design schemes, it still faces many challenges when widely applied. The complexity of the system leads to increased costs (for example, ALA requires multi-motor coordination), the challenge of high reliability requirements, and the difficulty of maintenance. In addition, different vehicle models require different designs and experiments, which consume a large amount of funds and have high research and development costs. This makes it difficult for some designs to be popularized in the passenger car and commercial vehicle markets at present. However, with the continuous advancements in materials science (such as shape memory alloys), intelligent control algorithms (such as adaptive fuzzy control and AI-driven optimization), and sensor technology, active aerodynamic systems are expected to make breakthroughs in the directions of intelligence, lightweighting, and integration. Active aerodynamic components not only need to be continuously deepened in the high-performance field, but also accelerate their penetration into the passenger car market, injecting continuous impetus into the multi-dimensional improvement of future automobiles in terms of performance, efficiency and safety.

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