A Review of the influence of active aerodynamic tail on vehicle handling stability

Wei Yu, Wei Gao*
Hubei Key Laboratory of Automotive Power Train and Electronic Control, Hubei University of Automotive Technology, Shiyan, China

*Corresponding author e-mail: gaow_qc@huat.edu.cn

Abstract. In order to improve the safety of road vehicles, various active safety systems have been proposed and developed. These active safety systems include active forward/backward steering, differential braking, active roll moment control, etc. In essence, the longitudinal, transverse and vertical dynamics of the vehicle are controlled from the perspective of tire mechanics, which has the disadvantage that the tire is easy to be saturated under limit conditions. This paper summarizes the control schemes of active aerodynamics to improve vehicle handling stability. When the vehicle is running at high speed, aerodynamics has a great influence on the vehicle, which greatly reduces the handling stability of the vehicle. Low handling stability may lead to unstable motion patterns. In order to improve the lateral stability, various control schemes considering relevant performance measures are designed and evaluated by numerical simulation or experimental methods. This paper focuses on the active aerodynamic control scheme, analyzes its characteristics, and determines the future research work.

1. Introduction
In order to improve the safety of vehicles, the U.S. government formulated FMVSS 126 standard [1]. In the past decades, various active safety systems have been proposed and developed to improve vehicle handling and stability, such as active steering, differential braking, active roll moment control, etc. [2-4]. They all work based on the longitudinal force of the tire, which has the disadvantage that the tire is easy to saturate under the limit working condition [5]. Therefore, the capability of the current active safety system can not exceed the performance limit determined by the interaction between tire and road, and the ability to improve vehicle handling and stability is limited.

At present, the tail is a common device in the vehicle. In recent years, many technologies have been explored to analyze and control the tail to improve the aerodynamic performance of the vehicle. Under different working conditions, the tail is adjusted by active control, so that the vehicle can obtain good aerodynamic performance. At low speed, the attack angle of the tail is adjusted to reduce the air resistance and improve the fuel economy of the whole vehicle; At braking condition, the attack angle of the tail is appropriately utilized to increase the windward area and air resistance coefficient of the vehicle, so as to reduce the braking distance of the vehicle; At high speeds, the tail is adjusted to an suitable angle to increase the grip of the tires, in order to achieve torque balance and improve the lateral stability of the vehicle; the tail on one side of the vehicle is appropriately changed to generate additional yaw moment [6].
The rest of the paper is organized as following. The second section reviews the design and optimization of vehicle tail and the influence of tail on vehicle stability. In the third section, the influence of passive tail on vehicle aerodynamic characteristics is introduced. The fourth section summarizes the relationship between drag or lift and key system parameters, and the main control strategies used in active tail and active aerodynamics control system. Finally, the fifth section draws a conclusion.

2. Vehicle tail

The reason why a car can run on the road depends on the friction between the tires and the road, and sufficient ground adhesion is the premise of improving the power performance of the car [7]. Therefore, by installing a tail wing at the rear of the vehicle, it can provide greater downward pressure for the high-speed vehicle and increase the adhesion between the vehicle and the ground. So that the vehicle can achieve the better dynamic performance, and improve the aerodynamic performance and handling stability of the vehicle.

2.1. Tail design optimization

The tail was first used in aerospace, and the large lift drag ratio provided greater lift for the aircraft. In the 1960s, flip flop began to assist the formula. The installation of flip flop can provide 30% - 35% downforce for the car.

According to the different installation position, the flip wing can be divided into front wing and tail wing, and the airfoil parameters and fin combination are the key to the effective operation of the flip wing. In reference [9], the prototype and modification of NACA4424 airfoil were simulated. The trailing edge of the prototype was thickened appropriately, and then a new airfoil was formed with smooth curve from a certain position of chord length. The results showed that the lift drag ratio was significantly improved at any angle of attack and any wind speed. Then, six modifications of naca4412 were carried out, Numerical analysis and calculation of the prototype and six modifications (including changing the start position of the modification, the thickness of the trailing edge, the shape of the smooth curve, etc.) show that the modification can effectively improve the lift coefficient and lift drag ratio of the airfoil within a certain angle of attack, and the maximum increase of lift drag ratio is nearly 200%; the drag coefficient of the airfoil can also be reduced at a small angle of attack.

The design principle of the tail is to achieve the balance point of the maximum downforce and the minimum aerodynamic drag. That is, the best match of aerodynamic drag coefficient and negative lift coefficient. At present, there are three main methods to test aerodynamic drag coefficient and negative lift coefficient: wind tunnel test method, power balance method and numerical calculation method [10]. [11] The numerical simulation method is used to analyze and compare the structure parameters of the tail of the car, such as airfoil, angle of attack and ground clearance. According to the change law of drag coefficient and negative lift coefficient and the matching principle, the installation scheme of the tail is determined. The results show that the airfoil with larger curvature and thicker airfoil body will produce greater lift. The optimal attack angle is 45 ° and the optimal ground clearance is 88 mm.

Tailing design optimization is the basis of active tailing research, which can effectively improve the aerodynamic characteristics of vehicles by selecting appropriate tailing. Therefore, it is necessary to use computational fluid dynamics technology to design and optimize the tail to improve the aerodynamic performance of the vehicle.

2.2. Influences of tail on vehicle stability

The tail wing device can increase the surface pressure of the car body, increase the adhesion between the tires and the ground, change the flow field at the rear of the car, and reduce the lift caused by the airflow whirling at the rear, so that when the car is driving at high speeds, the phenomenon of "floating" due to the weak adhesion at the rear will not occur [12].

In reference [13] the aerodynamic characteristics of racing car with or without aerodynamic package were compared with numerical analysis and experiment. The results show that the car with aerodynamic package increases the downforce by 650N compared with the car without empty cover, and have certain
advantages under the conditions of linear acceleration and zigzag ring. Therefore, the vehicle equipped with aerodynamic package can significantly improve the performance of the whole vehicle [14]. The virtual prototype model of the vehicle is established and the aerodynamic characteristics are considered. According to the lift drag characteristics of the tail at different angles of attack, the performances of the tail at different angles of attack are compared. Increase of attack angle can improve the transient response performance and crosswind stability of the car, but the insufficient steering characteristics of the car [15]. This paper analyzes the influence of the angle of attack of the rear wing on the curve performance, and finds that the increase of the angle of attack of the rear wing can weaken the tendency of excessive steering, which is beneficial to the performance of the car in the curve.

3. Influence of passive tail on vehicle
Since the 1960s, the tail has been helping F1 cars. It is a very important aerodynamic package in Car Aerodynamics. Compared with the shape resistance, the resistance of the vehicle with the tail can be ignored. At the same time, the tail provides greater downward pressure for the vehicle, increases the adhesion between the tire and the ground, helps the car traction, braking and cornering, and improves the safety and stability of the vehicle [16].

The passive tail is fixed at the tail of the car, which has poor adaptability and only has a good effect on a certain working condition. When the tail wing is installed at the end of the body (Fig. 1), it eliminates the turbulence generated by the rear of the vehicle. Compared with the vehicle without the tail wing, the aerodynamic resistance is reduced and the stability of the vehicle is improved [17]. The effects of changing the tail (-10, -5, 0, 5, 10) on the downforce and drag were studied by computational fluid dynamics (CFD). The results show that when the angle of attack is 5 degrees, the drag coefficient of the vehicle is the smallest, and it is the best for the straight line condition [18].

The installation of tail wings in the tail of passenger cars has gradually become a mainstream (Figure 2). It can provide a large downforce for the vehicle and increase the grip of the tire, so as to improve the safety and handling stability of the vehicle [19].
the stability of the vehicle to install the tail in the rear of vehicle. V. Shukla and G. Saxena [20] carried out a study. Comparative results between the baseline car and car with spoilers are shown in Table 1.

Table 1. Drag and lift coefficients of passenger cars with or without fins

| Configuration          | Drag coefficient | Reduction from base model(%) | Lift coefficient | Reduction from base model(%) |
|------------------------|------------------|------------------------------|-----------------|------------------------------|
| Base model             | 0.60             | 0                            | 0.25            | 0                            |
| Splines and rear spoiler | 0.51             | 15%                          | 0.22            | 12%                          |

4. Active aerodynamic control

Active aerodynamics control is a kind of vehicle for active safety control. The tail wing is installed at the tail of the vehicle, and the vehicle sensors are used to receive various state data when the vehicle is running, and the ECU is used to analyze and judge the data, so as to realize the mechatronics of the tail wing [21]. Finally, the aerodynamic performance of the vehicle is changed by the change of the attack angle of the tail.

4.1. Aerodynamics

The establishment of aerodynamic modeling is another necessary step in the development of active pneumatic control system. The drag and lift equations are usually derived from the following equation:

\[
\text{Drag} = C_D \rho A \frac{v^2}{2} \quad (1)
\]

\[
\text{Lift} = C_L \rho A \frac{v^2}{2} \quad (2)
\]

Where \(C_D\) and \(C_L\) are aerodynamic coefficients, \(\rho\) is air density in kg / m³, \(A\) is aerodynamic surface area in m², and \(V\) is the relative velocity of wind and aerodynamic surface in the above equation. In the case of moving surfaces, the angle of surface movement is a factor of aerodynamics. The force in this case is given by

\[
\text{Drag} = C_D \rho A \frac{v^2}{2} \alpha \quad (3)
\]

\[
\text{Lift} = C_L \rho A \frac{v^2}{2} \alpha \quad (4)
\]

\(\alpha\) is the angle of attack. Moreover, most importantly, the aerodynamic coefficients are not constant. They are also a function of the angle of attack. This fact is not realized in [22]. However, this aerodynamic characteristic was considered in later development, but the implementation of control system design was not introduced. Recent papers have fully recognized this point, and put forward the usual method.

4.2. Active tails

The fixed angle of attack tail can not be adjusted according to the situation of the track, and the aerodynamic performance of the vehicle is limited under different conditions. The 2011 F1 Championship introduced an electrically adjustable tail for the first time. When the car is accelerating in a straight line, there will be a certain gap between the wings by reducing the angle of attack of the wings. Most of the air flow out of the gap between the wings of the tail, and the downforce and air resistance will be reduced. When the car high-speed cornering, prone to sideslip, need to increase the grip, at this time, through the electric control system, increase the tail angle of attack, vehicle downforce increases, make the car safe cornering.

Literature [23] analyzed the aerodynamic characteristics of vehicles with different attack angles. The results show that when the attack angles of the tail are 5.5/24/28, 5.5/28/32 and 5.5/34/38 respectively, the lift drag ratio decreases with the increase of the attack angle of the flap in the tail assembly. Therefore,
when the car is cornering, increasing the attack angle of the tail will increase the downforce on the car. Although it will improve the car's cornering stability, it will also increase the trend of vehicle cornering and understeer. Electrically adjustable tail (DRS) has limited ability to improve vehicle lateral dynamics.

In recent years, some scholars gradually began to study the detachable adjustable tail, which has a certain impact on the longitudinal, transverse and vertical dynamics of road vehicles. By controlling the angle of attack of the left/right part of the split tail, the corresponding yaw moment can be obtained to ensure the lateral stability of the vehicle. [24] et al. Conducted a simulation test, and the results showed that the handling stability of the car equipped with active aerodynamics system was enhanced (Fig. 3). The results show that high downforce and bottom drag can be obtained when the attack angle of left/right tail is controlled in the range of 10~15.

[25] To improve the safety of high-speed vehicles, action detachable tail is installed at the tail of passenger cars (Fig. 4). Mohammed Hammad and khimar Qureshi et al. [26] installed a split tail in the rear of the car, and based on the linear quadratic regulator to control the attack angle of the left and right tail, to ensure the vehicle has good handling stability. Wu Yiwan proposed a vehicle stability control method based on the coordination of active pneumatic control and hydraulic differential braking. [27] On the basis of Mira standard model, two wing plates with airfoil type 4412 are selected as the active aerodynamic mechanism, and the active wing plate is installed on the top of the vehicle to generate the aerodynamic force/torque of the vehicle by actively controlling the angle of attack of the two wings.

4.3. Control strategies
The design and strategy of the control system may be the key to the development of active pneumatic control system. Accurate development based on vehicle dynamics and expected goal is the basic feature of active pneumatic control system. This section provides a brief overview of the control methods and strategies used over the years. In [28], there are two different strategies, that is, full state feedback and open-loop feedback. It is suggested to use prefilter and the combination of them to calculate the demand.
for roll and yaw actuators. Another look-up table, shown in Figure 5, is used to estimate the angles of attack of two wings, four in the case of [29], in order to generate the required forces. The second part of the control system consists of a PID controller, which is used to move the actuator to make the wing rotate at a given angle of attack.

![Example of lookup representation used in active pneumatic control system](image)

5. Summary

In the past twenty years, more and more researches have been done on the active pneumatic control system. Published research results show that the active pneumatic control system can significantly improve the longitudinal, vertical and lateral dynamics of highway vehicles. In addition to the streamlined body design, the active aerodynamic surface can further reduce the aerodynamic drag, thus improving the acceleration performance and fuel economy of the vehicle. Active pneumatic control has proposed a variety of control strategies, including PID, LQR and so on. In recent years, robust control techniques such as H infinity have been used to control active spoilers. These control strategies have been successfully implemented to varying degrees. Previous research on active pneumatic control paves the way for the further development of the technology in this field.

In past research on active aerodynamic control, few attempts have been made to the coordinated control between active aerodynamic control and active steering, differential braking, torque vector or pneumatic hydraulic control. It is expected that coordinated aerodynamic control can greatly improve the stability and safety performance of existing active safety systems. It is necessary to combine computational fluid dynamics (CFD), controller and multi-body vehicle system model through co-simulation. Effective co-simulation can study the influence of aerodynamics and control strategy on vehicle dynamics. Physical prototypes of active pneumatic control systems are rarely manufactured, and limited wind tunnel test data used to verify aerodynamic control are reported. In order to promote the active aerodynamic control technology, it is necessary to further study the manufacture of physical prototype and wind tunnel test.
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