Drive control strategy of two-wheel independent drive electric vehicle

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Abstract. According to the advantages of two-wheel independent drive electric vehicle that the torque and rotational speed of the drive wheel can be easily measured, a driving control strategy of driving antiskid control and torque coordination control is proposed based on road surface identification slip rate and adhesion coefficient. The principle of road surface identification is given. According to the signals of wheel speed sensor, lateral acceleration, longitudinal acceleration and torque sensor, the wheel slip ratio, road surface adhesion coefficient, vertical force and longitudinal force are calculated. Combined with μ-S function curve proposed by Burckhardt et al., the road surface adhesion coefficient and optimal slip ratio are identified. Driving antiskid control strategy adopts PID control technology based on road surface identification of optimal slip rate, peak adhesion coefficient and optimal slip rate, which mainly includes four parts: establishment of wheel stress model of two-wheel independently driven electric vehicle, approximate calculation of slip rate and road adhesion coefficient, optimal slip rate estimation based on fuzzy control and PID controller design based on optimal slip rate. The torque coordination control adopts PID control method based on ideal yaw rate.

1. Introduction
In the current world, in order to respond to the energy and environmental crisis, new energy technologies have received increasing attention. As an important part of the new energy field, the development and progress of electric car has important significance of the times. Similar to conventional gasoline vehicles, electric car can use motor traction control to improve the driving performance of the vehicle and improve the driving safety of the vehicle. [1] Based on the characteristics of the drive motor that can directly control the output torque, this paper discusses a control strategy for electric vehicle driving antiskid and driving safety with the goal of two-wheel independent driving of electric vehicles.

The main purpose of the electric vehicle drive antiskid control is to reduce the phenomenon of excessive slipping of the driving wheels when the vehicle is driving on various roads, in order to improve driving safety and make full use of the performance of the driving motor. The principle is to control the real-time slip rate near the optimal slip rate when the drive wheel is slipping, thereby making full use of the ground adhesion and improving the stability of the vehicle. Two-wheel independent driving electric vehicles have independent control over the driving torque of each driving wheel, and the motor torque and wheel speed can be easily measured. Therefore, it has obvious control advantages over conventional vehicles in terms of driving antiskid control.

In terms of the research on the key technologies of the two-wheel independent drive electric vehicle control, there have been many related studies on driving antiskid and torque coordinated control, but generally it is studied as a separate control strategy, there is less research on combining multiple methods...
for comprehensive control If the control functions of the two cannot be organically unified[2], it will be difficult to meet the requirements for normal driving of two-wheel independent-drive electric vehicles on actual roads under complex conditions, which seriously restricts the practical application and development of two-wheel independent drive electric vehicle.

In this regard, a drive control strategy for the synergy of drive antiskid control and torque coordinated control for two-wheel independent drive electric vehicles was proposed by this paper. Drive antiskid control based on optimal slip rate identification and PID control is adopted to prevent electric vehicles from excessive slip after entering the road with low adhesion coefficient, the torque coordinated control based on the ideal yaw angular velocity is adopted to control the yaw motion of the vehicle and improve the dynamic performance and running stability of the two-wheel independent drive electric vehicle.

2. Drive antiskid control strategy

2.1. Road identification method

Electric vehicles have their own optimal slip rates on pavements with different adhesion coefficients. The Acceleration Slip Regulation is based on the optimal slip rate for real-time optimal control. Therefore, the road must be identified in real time.[3]

When the car is running, the slip rate of the road surface and the actual utilization adhesion coefficient are estimated in real time according to the longitudinal acceleration, lateral acceleration, wheel speed, angular acceleration, motor torque and other information measured from various sensors of the vehicle.

Then, the slip rate and the actual utilization adhesion coefficient are inputted into a road surface database containing 6 standard road surfaces for comparison, and are identified by a fuzzy controller. After the road condition is determined, the optimal slip rate $S_{opt}$ and peak adhesion coefficient $\mu_{max}$.

2.1.1. Calculation of Wheel Slip Rate of Driving Wheel

The vehicle speed $v$ is obtained from the average of the speeds of the non-driven front wheels, and the slip ratio of its two rear drive wheels is:

$$v = \frac{\omega_1 R + \omega_2 R}{2}$$

$$S_i = \frac{\omega_i R - v}{\omega_i R}$$

In the above formula, $v$ is the longitudinal vehicle speed at the center of mass of the vehicle, $\omega_i$ and $\omega_2$ are the angular velocities of the two front wheels of the vehicle, and $R$ is the wheel rolling radius; $S_i$ is the slip ratio of the driving wheels, $\omega_i$ is the angular velocity of the two driving wheels, where $i \in \{3, 4\}$ representing the two rear wheels.

2.1.2. Calculation of Vertical Force

Considering the influence of longitudinal and lateral acceleration of the vehicle on the vertical force, the vertical force of the two rear wheels can be calculated by the equation 3

$$F_{z,i} = \left[ \frac{1}{2} mg + ma_y \right] \frac{h}{d_r} + \frac{l}{2} ma_x \frac{h}{I}$$

In the above formula, $F_{z,i}$ is the vertical force of the two driving wheels, $m$ is the mass of the whole vehicle, $g$ is the gravitational acceleration, $a_y$ is the lateral acceleration at the center of mass of the
vehicle, $h$ is the centroid height, $d_r$ is the wheelbase of the rear wheels, $l$ is the wheelbase of the front and rear axles, and $a_x$ is the longitudinal acceleration at the center of mass of the vehicle.

2.1.3. Calculation of Vertical Force

The longitudinal force between the tire and the road surface when the vehicle accelerates can be obtained according to the equation 4:

$$J a_i = T_i - F_{x,i}$$

In the above formula, $J$ is the moment of inertia of the two drive wheels and $\alpha_i$ is the angular acceleration of the two drive wheels. $T_i$ is the driving torque of the two driving wheels, $F_{x,i}$ is the longitudinal force of the two driving wheels.

2.1.4. Calculation of Vertical Force

The coefficient $\mu$ can be calculated using the following formula:

$$\mu_i = \frac{F_{x,i}}{F_{z,i}}$$

(5)

2.2. Pavement Identification Based on Fuzzy Control

2.2.1. Calculation of pavement adhesion coefficient and optimal slip rate

In order to quickly and accurately estimate the current pavement utilization adhesion coefficient and the optimal slip ratio, the fuzzy control method is used to identify the current pavement. The road surface identification part compares with the standard road surface curves in the module through fuzzy logic reasoning according to the wheel slip rate and the road surface utilization adhesion coefficient, judges the similarity between the corresponding points $(S, \mu)$ of the current road surface and each standard road surface and obtains the corresponding similarity degree, and then estimates the optimal slip rate and the peak road surface utilization adhesion coefficient of the current road surface through the weighted average of equation 6 and equation 7.[4]

$$S_{\text{opt}} = \frac{\sum k_i S_{\text{opti}}}{\sum k_i} , \quad i = 1, 2, 3, 4, 5, 6$$

(6)

$$\mu_{\text{max}} = \frac{\sum k_i \mu_{\text{maxi}}}{\sum k_i} , \quad i = 1, 2, 3, 4, 5, 6$$

(7)

In the above formula, $S_{\text{opti}}$ and $\mu_{\text{maxi}}$ are the optimal slip ratio and peak road utilization adhesion coefficient of 6 standard road curves respectively.[5] And $k_i$ is the degree of similarity with a standard road surface curve obtained through fuzzy logic reasoning.

2.2.2. Selection of Standard Road Curves

The standard road curve can adopt the $\mu-S$ curve function expression proposed by Burckhardt et al.

$$\mu(S) = C_i \left(1 - e^{-c S}\right) - C_j S$$

(8)

$S_{\text{opti}}$ and $\mu_{\text{maxi}}$ of different road surfaces can be obtained by equation 9 and equation 10.
Six of the seven standard pavements given by Burckhardt are selected as comparative pavements, and dry asphalt, dry cement, wet asphalt, wet pebbles, snow and ice are arranged from high to low according to the peak pavement adhesion coefficient.

Table 1. Pavement database with 6 standard pavements

| pavement       | C1   | C2   | C3   | \( S_{opt} \) | \( \mu_{max} \) |
|----------------|------|------|------|--------------|-----------------|
| Dry Asphalt    | 1.28 | 23.99| 0.52 | 0.17         | 1.17            |
| Dry cement     | 1.20 | 25.17| 0.54 | 0.16         | 1.092           |
| Wet Asphalt    | 0.86 | 33.82| 0.35 | 0.13         | 0.80            |
| Wet Pebble     | 0.40 | 33.71| 0.12 | 0.14         | 0.34            |
| Snow           | 0.19 | 94.13| 0.06 | 0.06         | 0.19            |
| Ice            | 0.05 | 306.4| 0.001| 0.03         | 0.05            |

2.2.3. Design of Pavement Identification Controller

The input of the controller is the actual slip rate \( S \) of the left drive wheel or the right drive wheel and its corresponding \( \mu \). Through the process of fuzzification, fuzzy logic reasoning and anti-fuzzification, the similarity \( k_i \) with 6 standard pavement curves is output, and then the optimal slip rate and peak pavement adhesion coefficient of the current pavement are calculated by weighted average. Fuzziness Two fuzzy subsets covering the whole fuzzy universe are selected to fuzzify the input slip rate \( S \), which is divided into small slip rate and large slip rate. At the same time, six standard pavements are divided into "ice", "snow", "wet pebbles", "wet asphalt", "dry cement" and "dry asphalt" respectively in the small slip rate area and the large slip rate area.[6]

2.3. Design of PID controller based on optimal slip rate

2.3.1. Overall design idea of driving anti-skid control strategy

The control methods often used in the research of motor controllers are: sliding mode variable structure control, PID control, fuzzy control, neural network control, adaptive fuzzy neural control, etc. In view of the advantages of easy measurement and control of electric vehicle speed and torque, a real-time control strategy to control the drive wheel slip rate near the optimal slip rate has become the focus of electric vehicle research.

The control strategy of two-wheel independent driving electric vehicle driving antiskid is shown in the figure. The driver steps on the accelerator pedal to give the target torque to control the starting or acceleration of the electric vehicle. Vehicle acceleration sensors, wheel speed sensors, etc. send the corresponding signals to the slip rate calculation module and the road adhesion coefficient calculation module for calculation. The pavement recognition module recognizes the road surface based on the input real-time slip rate and the actual use of the adhesion coefficient, and calculates the optimal slip rate and the peak road adhesion coefficient after identifying the current road surface.

In this paper, a PID controller is used to control the driving torque based on the difference between the input actual slip rate and the optimal slip rate, and the drive wheel slip rate is controlled near the optimal slip rate.[7] When the difference between the road surface peak adhesion coefficients output from both sides exceeds a preset threshold, the driving torque distribution module will consider the vehicle to be driving on a target road and automatically switch to the driving torque driving antiskid
control mode to prevent dangerous conditions such as deviations in the car, make the car run more stably.

![Diagram of drive antiskid control strategy for two-wheel independent electric vehicles](image)

2.3.2. PID drive anti-slip controller
The key to the PID control module is the PID controller. The PID controller is a linear regulator that linearly combines the ratio (P), integral (I), and derivative (D) of the deviation between the input value and the actual output value. The method constitutes a control amount, and controls the control amount. PID antiskid controller uses the optimal slip rate as the control target. By adjusting the motor torque within the range of the target torque input by the driver, the actual slip rate $S$ can be controlled in real time near the optimal slip rate. The input of PID is $\Delta S = S - S_{opt}$, and the output is the adjustment torque of the motor.

$$T_{cont}(t) = K_p\Delta S(t) + K_i\int \Delta S(t) dt + K_d\frac{d\Delta S(t)}{dt}$$  \hspace{1cm} (11)

In the above formula, $K_p$ is the proportional gain, $K_i$ is the integral coefficient, and $K_d$ is the differential coefficient. $T_{cont}$ is the adjustment torque output by the PID controller.

3. Torque coordinated control
Since the linear two-degree-of-freedom model takes into account the vehicle yaw and side-slip motion and can reflect the linear relationship between the driver's steering input and the vehicle yaw angular velocity, the linear two-degree-of-freedom model is used to calculate the ideal yaw angular velocity $\gamma^*$ (12)[9]

$$\gamma^* = \nu\delta'\left[\frac{L(1 + K\nu^2)}{m(a/k^2 - b/k)}\right]$$ \hspace{1cm} (12)

In the formula, $K$ is the stability factor, $K = m(a/k^2 - b/k)/L^2$, the $K$ value is 0.005.

The yaw angular velocity controller takes the ideal yaw angular velocity as the control target, and constantly adjusts the output torque of the motor to finally control the vehicle's yaw angular velocity near the ideal yaw angular velocity. The controller adopts the PID control method, that is, taking the input yaw angular velocity deviation $\Delta\gamma' = (\gamma^* - \Delta\gamma')$ as the closed-loop control target, to regulate and control the motor torque. The torque calculation formula is as shown in formula (13):
\[ T_{\text{com}2}(t) = K_p \Delta \gamma(t) + K_i \int \Delta \gamma(t) \, dt + K_d \frac{d \Delta \gamma(t)}{dt} \]  \hspace{1cm} (13)

In the above formula, \( K_p \) is the proportional gain, \( K_i \) is the integral coefficient, and \( K_d \) is the differential coefficient. \( T_{\text{com}2} \) is the adjustment torque output by the PID controller.

4. Analysis of electric vehicle operation

Due to the complicated situation of the running car, the vehicle speed is analysed in three stages, and the speed is roughly divided into acceleration at start (0 to 36 km/h), medium speed (36 to 72 km/h), and high speed (over 72 km/h) 3 stages.[10]

At the start of the car, the speed is extremely low. Even if the longitudinal adhesion capabilities of the drive wheels on both sides are quite different, it has a weak impact on the lateral stability of the car. The driver has time to control the steering wheel to keep the car straight. So the biggest goal at this stage is to increase the power of the car so that the car can start as soon as possible. At this time, the real-time slip rate is controlled near the optimal slip rate to make full use of the current peak adhesion coefficient of the road surface to ensure the power performance of the car and make the car start stably.

The medium-speed running process is the stage where the car is driving for the longest and the vehicle speed changes the most frequently. The medium-speed stage should be based on ensuring lateral stability and improving the power of the electric vehicle as much as possible to meet the driving needs of the car on different roads and the driving intention of the driver. For a medium-speed car, if the driving forces of the driving wheels on both sides are significantly different, the car is extremely prone to instability such as side slip and tail flick on bad roads, which will seriously damage the safe operation of the car. At this time, the lateral stability of the car must be ensured first, so as the speed increases, the real-time slip rate should be gradually reduced, so that the longitudinal and lateral adhesion coefficients of the drive wheels are in a high range to ensure the stability of the car at medium speed while taking into account the power, to ensure driving safety.

For a high-speed car, due to the high speed, if the driving forces of the driving wheels on both sides are slightly different, the car is prone to dangerous situations such as side slip and tail flick. For cars driving at high speed, driving safety should be given top priority. Therefore, the main control objective of the Acceleration Slip Regulation is to ensure the lateral stability of the car to ensure the safety of the car.

5. Conclusion

Based on the advantages of easy measurement of the torque and rotational speed of the driving wheels of two-wheel independent driving electric vehicles, this paper designs a acceleration slip regulation based on road surface recognition. By identifying the road surface adhesion coefficient and the optimal slip rate, the PID controller can control the real-time slip rate of the drive wheels near the optimal slip rate. A road recognition algorithm was designed, and the sensors equipped with the vehicle were used to measure signals such as longitudinal acceleration, lateral acceleration, wheel speed, and torque.

By calculating the slip rate, vertical force and longitudinal force of the driving wheel, combined with the \( \mu-S \) function curve proposed by Burckhardt, A better identification of the road surface on which the driving wheel is located and its optimal slip rate is achieved. At the same time, combined with the PID anti-skid strategy and torque coordinated control, the two-wheel independent driving electric vehicle is comprehensively controlled, and the vehicle's coping method under different speed forms is analyzed. Design a control strategy for two-wheel independent drive electric vehicles to make full use of motor drive performance and improve driving safety.

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